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HIGH-QUALITY MUON BEAM PRODUCTION BASED ON SUPERCONDUCTING SOLENOIDS

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Abstract

In labs, muon beams are produced by protons hitting targets. The initial phase space of the muon beam is extremely large. In general, two types of muon collection methods have been used in the world. One is to put the muon production target in a superconducting solenoid, and low-energy muons are collected from the back of the target, then transported through a bent solenoid. In this way, a high-intensity muon beam can be collected, but the energy spread is wide and the beam polarization is low. For most μSR applications a surface muon beam with narrow energy bite and high polarization is required. Most μSR facilities are built with collecting magnets by the side of the target, in this way only a small fraction of muons with low emittance are collected and transported downstream. In this work we outline a muon collection method based on superconducting solenoid. Instead of using bent solenoids, a matching section with a dipole magnet is used to select muons with a certain momentum and match to downstream beamliines. A high-quality muon beam can be achieved with a high intensity and polarization. Such a method can be adapted to the MUSIC, Mu2e, and COMET muon beamlines after their dedicate experiments and convert the beamlines into a high quality μSR facility.

INTRODUCTION

Muons have wide applications in both fundamental particle physics and material science researches.

As a charged lepton in the second generation, the muon is a great tool to test the V-A structure in the weak interaction [1]. The Michel parameters of muon decay are used to precisely measure important constants to test the Standard Model [2]; the rare decay of muons is used in experiments to search for new physics [3].

When a μ^+ decays it emits a fast decay positron preferentially along the direction of its spin due to the parity violating decay. Based on this theory, the Muon Spin Rotation (μSR) technique is widely used in studying the electromagnetic characteristics of materials. As an exquisitely sensitive local probe, the muons can tackle fundamental problems in condensed matter physics and chemistry [4].

In labs, muons are produced by protons hitting targets. Most of the muon facilities around the world are based on powerful proton accelerators, and two types of collecting methods are used for the above applications. For particle physics experiments that require super-high muon intensity, dedicated muon beams are designed for the specific experiment [5, 6]. In this case, the muon production target is put inside a strong magnetic solenoid in order to reach the maximum acceptance for the diverged muons. Then the muons are transported to the experimental area in bent solenoids. Such a beamline has a great advantage to produce an intense muon beam. For example the MuSIC facility has reached an intensity of 4×10^8 μ^+/s with only a proton beam power of 400 W [7]. However, the energy spread of such a beam is large and the beam polarization is low, and these are required for μSR applications.

μSR application platforms are based on producing muons from a thin target, and collect the muons by room-temperature (RT) magnets from the side of the target. In this way, the transverse acceptance of the the beamline is relatively small and a narrow energy spread of the muon beam is selected in the beamline. High-quality muon beams can be obtained by this method but the muon production efficiency is sacrificed. At PSI in Switzerland, the most intensive surface muon beam ($4.2 \times 10^8 \mu^+$/s) in the world is produced by a 1.2 MW proton driver [8].

In this work we present a novel way to produce a high-quality muon beam with a relatively high efficiency. We combine the advantages of the above two methods: the production target is put inside a super-conducting magnet to collect the most of the surface muons; then a beamline with RT magnets will be designed to maximize the transverse acceptance and select a muon beam with a narrow energy spread. As an example we use the proton beam produced at the China Spallation Neutron Source (CSNS), we simulate the muon beam quality from the back (upstream of proton beamline) of the muon production target. We design a muon transportation line with a large transverse acceptance. At the end of the muon beamline, a muon beam with an intensity of $8 \times 10^7 \mu^+$/s is expected with a proton power of 25 kW. The beam polarization at experiments can reach above 0.9. The simulations in this work are all performed in G4Beamline [9].

PROTON BEAM AND TARGET STATION

CSNS provides a proton beam of 1.6 GeV energy. One bunch in every 10 double-bunch pulses is planned to be extracted to produce muons. In this work we consider a proton beam power of 25 kW on the muon production target, which is 5% of the total power of the CSNS II upgrade. The proton beam spot at the target is about 5.7 mm in rms radius. The graphite target is a 30 cm long cylinder with a diameter of 15 mm, sitting at the center of the major solenoid. Figure 1 shows the schematic design. The proton beam is injected to the target station and hit on the production target. The collecting magnet is a superconducting solenoid with a strong magnetic field up to 5 T. An adiabatic taper is designed for the downstream high-energy decay muon beams

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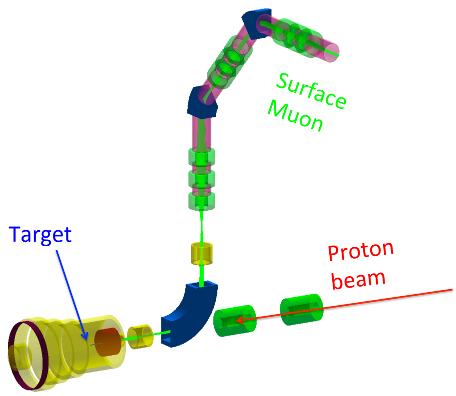

Figure 1: Schematic layout of the surface muon production and transportation.

and is not discussed in this paper. We collect the surface muons from the upstream of the target station. A muon transportation beamline is designed to deliver the surface muons to the experimental hall. According to the space limitation at the CSNS campus, we design the beamline to guide the muons to the second floor in the experimental hall.

A weak C-shape dipole magnet is placed between the proton beamline and the target station in order to bend the produced surface muons to the muon beamline. Because the surface muon momentum is much lower than the proton momentum, this dipole has negligible effect on the proton beam.

SURFACE MUON AND THE COLLIMATOR

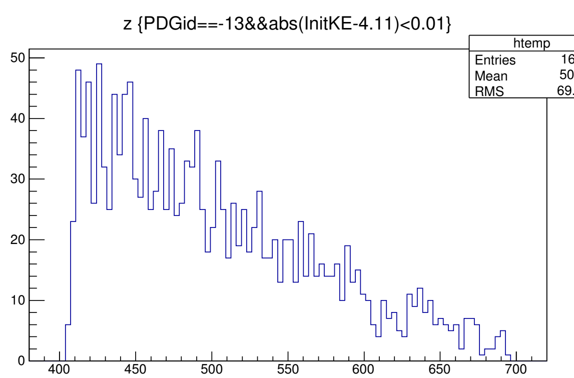

Figure 2: Initial distribution of the surface muons on the production target. Center of the target is at $z = 550$.

The surface muons are produced by pions decay at the surface of the target. The initial angular distribution of the surface muons is isotropic. However, because of the scattering by the target nuclei, the proton beam is expanded and the production efficiency is reduced along the target. Figure 2 shows the initial distribution of the surface muons along the target (center of the target is at $z = 550$). Most of the surface muons are produced at the first half of the target, and the geometry of the target will be optimized to increase the production efficiency accordingly.

The purity of the surface muon beam is important for the beam polarization. Cloud muons, which are produced by low-energy pions decaying near the target, reduces the beam polarization. They have the same/similar momentum with the surface muons but with low polarization, so it's hard to filter these "impurities" in the beamline. It's essential to kill the cloud muons in the beginning of the beamline.

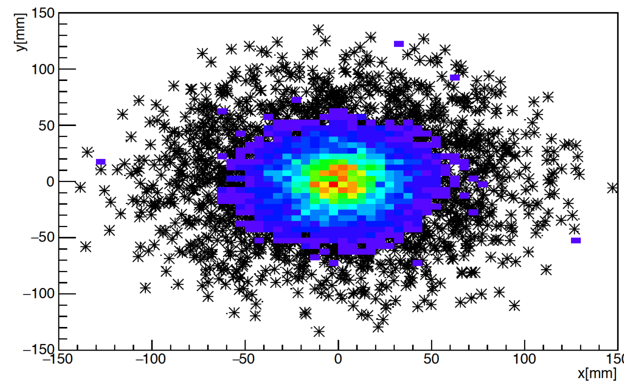

Figure 3: Transverse distribution of the surface muons (colored) and the cloud muons (stars) at the entrance of the target station.

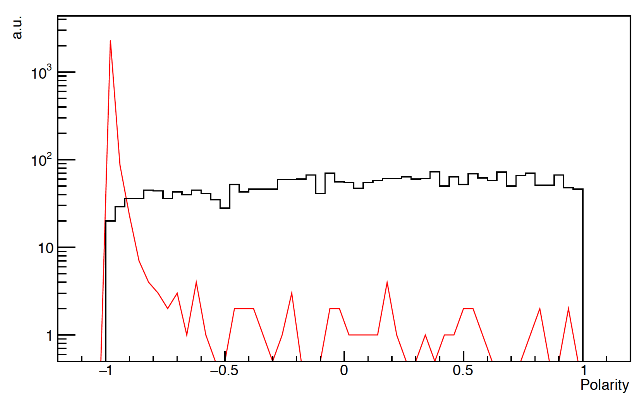

Figure 4: Polarization of the surface muons (red line) and the cloud muons (black histogram) at the entrance of the target station.

Figure 3 shows the transverse distribution of the surface muons (colored) and the cloud muons (stars) at the entrance of the target station. Here we only consider the muons in the momentum range between 26 MeV/c and 30 MeV/c (the standard range), because the muons with higher and lower momentum can not be accepted by the downstream beamline. From Fig. 3 we can see that the cloud muons distribute in large space because they are produced by pions in flight. These cloud muons has very poor polarization (< 0.1) comparing to the surface muons (> 0.98, see Fig. 4), and must

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be cleaned before they enter the beamline because they have the same momentum with the surface muons. The number of cloud muons is about 50% and the polarization of the muons in the standard range is about 0.42.

We put a collimator to filter the cloud muons (the red cylinder in Fig. 1). The collimator has an inner radius of 50 mm with a length of 350 mm. In this work any particles hitting the collimator are killed immediately. Further study will be carried out to investigate the detailed effect of the collimator.

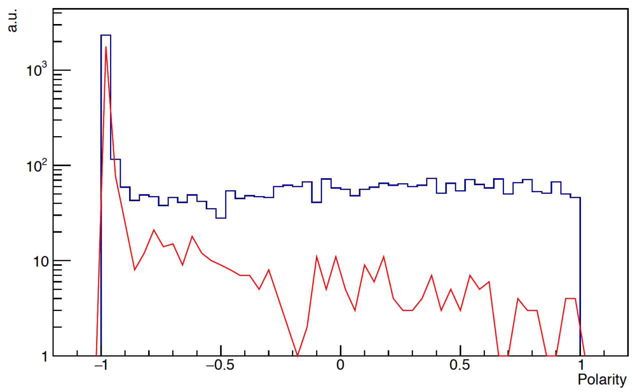

Figure 5: Polarization of the muon beam with (red line) and without (blue histogram) the collimation.

Figure 5 shows the beam polarization at the entrance of the target station with (red line) and without (blue histogram) the collimator. Although the collimator reduces a bit the number of the surface muons, it greatly increases the beam polarization to about 0.89. A large number of cloud muons are killed by the collimator and the proportion of cloud muons in the beam is reduced to 15%. The beam intensity after the collimation is $2 \times 10^9 \mu^+$/s with a transverse emittance of $12\,\pi$ mm rad.

TRANSPORTATION IN THE BEAMLINE

We designed a beamline with large transverse acceptance. A pair of solenoid magnets are used to match the surface muons to the downstream beamline. Because the 90° bending magnet introduces a strong focusing effect on the x direction, the muon beam is not symmetric after the matching section. So we use quadrupole triplets for the downstream beamline. The optic design of the beamline is not discussed in this paper. Here we report the beam quality at the experimental area with current preliminary design.

The beam intensity for experiments is about $8 \times 10^7 \mu^+$/s with a polarization of 0.93 within a beam rms size of 24×50 mm^2 (considering a proton driver power of 25 kW at 1.6 GeV). The momentum spread of the beam is about 8.5% in FWHM. The large beam spot is not suitable for μSR applications but could be used for slow muon production and particle physics experiments that don't need small beam size. Beam splitting will be considered to provide small beam size for several experiments.

Beam collimation is simulated to provide a small beam spot of 30×30 mm^2 (full beam size including 95% of all muons), and the beam intensity is reduced to $3 \times 10^6 \mu^+$/s. Such an intensity can fully fulfill the requirement of μSR applications.

SUMMARY

A novel method is presented to deliver a high intensity muon beam with high quality. We put the muon production target inside a superconducting solenoid to collect the maximum muons, and designed a muon beamline with large transverse acceptance to deliver the beam to the experimental area. We summarize the final beam parameters at experiments with and without the beam spot collimator in Table 1. Further study will be done to optimize this scheme.

Table 1: Beam Parameters for Experiments in Case of With and Without Beam Spot Collimator

	Without	With
μ^+ rate	$8 \times 10^7 \mu^+$/s	$3 \times 10^6 \mu^+$/s
Mean energy	4.1 MeV	4.1 MeV
$\delta p/p$ (FWHM)	8.5%	8.5%
Polarization	0.91	0.93
Beam size (rms)	24×50 mm^2	12×12 mm^2

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