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INTENSE MUON BEAMS FROM THE CSNS SPALLATION TARGET

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Abstract

Intense muon beams are useful for a wide range of physics experiments. Currently most of the muon beams are produced by protons hitting thin targets sitting upstream of spallation neutron targets. The intensity of the muons is greatly limited by the small thickness of the muon targets, which are intended to have minimum impact on the proton beams. When the majority of the proton beam hits the spallation target, a large number of pions/muons are produced. After being captured in a solenoidal magnetic field, a high intensity muon beam can be produced. In this paper we take the Chinese Spallation Neutron Source (CSNS) target as an example and investigate the production of high intensity muon beams. Two possibilities are presented in this paper: an upstream collection of surface muons and a downstream collection of pions which is followed by a decay and compress channel to obtain a high intensity muon beam. Simulations show both methods can reach high intensities which could significantly increase the statistics of many experiments.

INTRODUCTION

When protons hitting spallation targets, a large number of pions are produced along with the neutrons. Such pions can be collected to produce high intensity muon beams in decay channels. Such muon beams can be injected into storage rings for neutrino studies. They can also be used for rare-decay researches if their energies are reduced by rf cavities. When the pions decay on the surface of the target, a highly polarized, mono-energy muon beam can be produced, which is called "surface muon". Such surface muon beams can be used for the next generation μSR applications, muonium spectroscopy, as well as searches for muon rare decays.

In this paper we investigate the production of pions and muons on the Chinese Spallation Neutron Source (CSNS) target [1]. In order to have minimum impact on the neutron production, we outline two possible ways of collecting the pions and muons: collecting surface muons from upstream of the target and collecting pions from downstream of the target. We present the collecting efficiency depending on various solenoidal magnet settings. Simulation results show that with reasonable settings the collecting efficiency for the surface muons and the pions can reach $1.3\times10^{-5}\mu^+/proton$ and $5\times10^{-3}\pi^+/proton$ respectively. Based on the 500 kW proton driver with an energy of 1.6 GeV, a surface muon beam of $6.5\times10^{10}\mu^+/s$ and a pion beam of $2.5\times10^{13}\pi^+/s$ can be reached at the end of the collecting solenoid. Such a surface muon intensity is on the same level as the planned HiMB project [2] at Paul Scherrer Institute (PSI).

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For the collected pions downstream, we implement the front end [3] concept of the Neutrino Factory/Muon Collider to compress the momentum spread, and then decelerate the muons from pion decay to low energy so that they can be used for various experiments. Preliminary simulations based on G4beamline show a muon rate of $2\times10^{12}\mu^+/s$ can be reached with muon momentum lower than 75 MeV/c. Such an intense muon beam can significantly increase the statistics of many muon experiments such as Mu2e [4], Mu3e [2], etc.

COLLECTING SCHEME

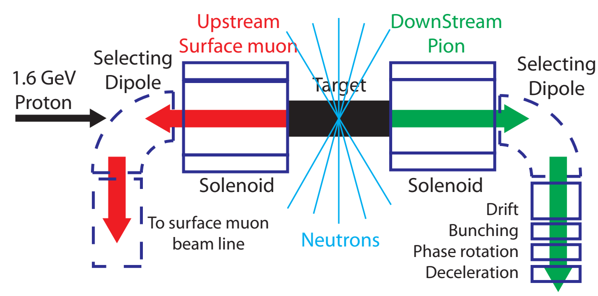

Figure 1: Scheme of collecting the surface muons upstream of the target and collecting the pions downstream.

Figure 1 shows the collecting scheme. The proton source has an rms size of 80 mm × 30 mm on the target. The geometry of the tungsten target is 170 mm in width, 70 mm in height and 570 mm in length. We put collecting solenoids upstream and downstream to focus the muons and pions that are produced in the target. In this way we minimize the influence on the neutron beams. Selecting dipoles can be implemented to guide the beams to further beam lines. In this paper we focus on the collecting efficiency of various settings of the collecting solenoids and implement the front end concept of the Neutrino Factory/Muon Collider to compress the muon momentum spread.

SURFACE MUONS

Figure 2 shows the momentum distribution of the surface muons on the upstream surface of the target. The spectrum has a peak at 28 MeV/c with a sharp cut at high momentum, representing the muons that decay right on the surface of the target. The stopped pions that decay inside but close to the surface of the target produce the muons with lower momentum. The higher momenta muons are produced by the pions that decay in flight. The production efficiency of the surface muons (p < 30 MeV/c) is $3.6\times10^{-5}\mu^+/proton$ on the target surface.

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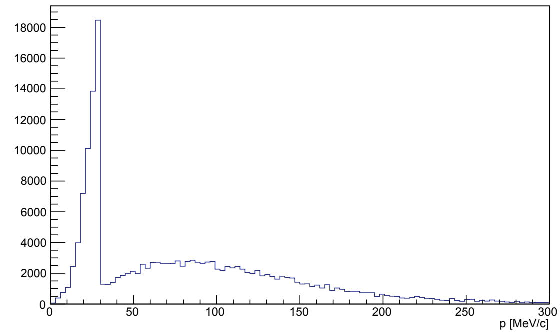

Figure 2: Momentum distribution of the surface muon on the upstream surface of the target.

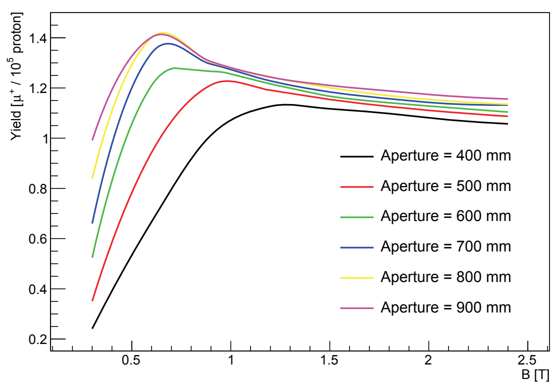

Figure 3: Surface muons yield versus the field strength of the collecting solenoid with different apertures.

We put a 3 m long straight solenoidal magnet right in front of the target to collect these intense surface muons. We first investigate the collecting efficiency depending on the magnet aperture and the field strength. Figure 3 shows the surface muons yield as a function of the field strength of the collecting solenoid with different apertures. The best collecting is a large aperture solenoid with 0.6 T magnetic field. Stronger field does not increase the yield of the surface muon, but only increases the acceptance of high-energy muons. Considering the proton beam pipe aperture of 700 mm, a collecting solenoid with the same aperture can reach a surface muon rate of $1.35 \times 10^{-5} \mu^+/proton$ at the end of the collecting solenoid.

We chose a 700 mm aperture solenoid to investigate the survival probability of the surface muons along the solenoid. Figure 4 shows the surface muon survival probability as a function of the distance from the surface of the target. About 50% of the surface muons are lost in the first 400 mm. Better collection with higher efficiency can be achieved by using a toroidal magnetic field. This work will be done in the future.

The position of the collecting solenoid is also important to the collecting efficiency. Figure 5 shows the survival probability of the surface muons as a function of the gap distance between the collecting solenoid and the target. The

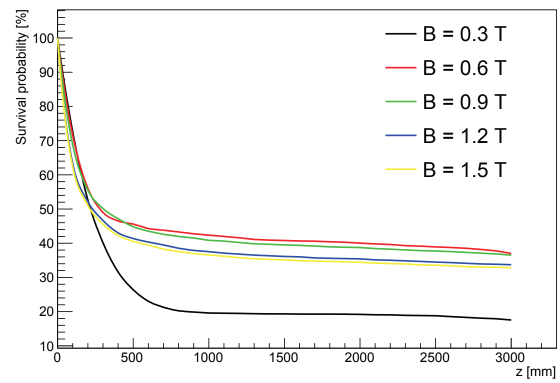

Figure 4: Survival probability of the surface muons versus the distance from the surface of the target. Solenoid aperture = 700 mm.

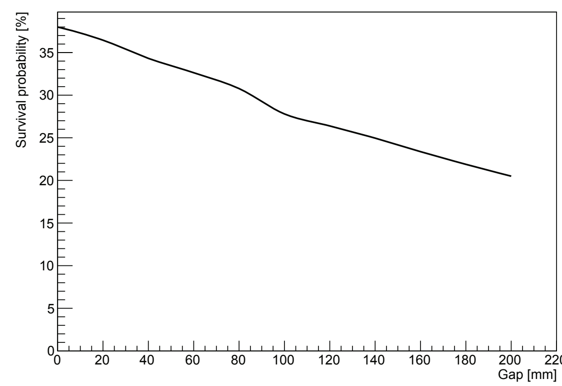

Figure 5: Survival probability of the surface muons as a function of the gap distance between the collecting solenoid and the target. Solenoid aperture = 700 mm; B=0.6 T.

collecting efficiency decreases almost linearly as the gap increases. A gap of 200 mm will cause 50% more beam loss.

PIONS

At the downstream side of the target, a large number of high-energy pions shoot out before decay, so it is better to collect this pions instead of surface muons. The production rate of the pions on the downstream surface of the target is $0.025\pi^+/proton$. The momentum distribution of the pions has a peak around 300 MeV/c, with a large spread. Such pions need to be collected in a stronger magnetic field with a large aperture.

We put a 3 m-long solenoid right after the target, and varying the aperture and the field strength of the magnet to find out the best collecting efficiency. Figure 6 shows the pion yield at the end of the solenoid as a function of the field strength. The highest efficiency is reached by using a large aperture solenoid with a magnetic field of 7 T. Stronger field does not increase the yield because of the large angular

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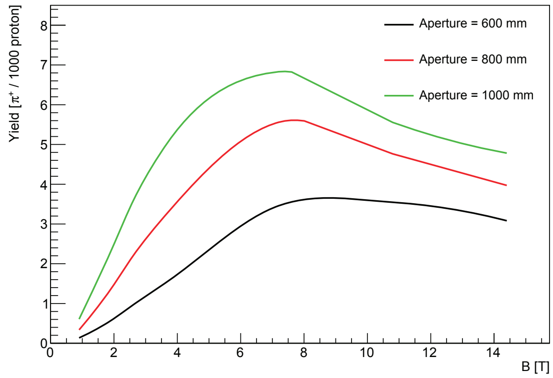

Figure 6: Pion yield versus the field strength of the collecting solenoid with different apertures.

divergence of the pion beam. About 80% of the pions are lost in the first 500 mm in the solenoid. Better collecting methods will be investigated in future work.

COMPRESSION

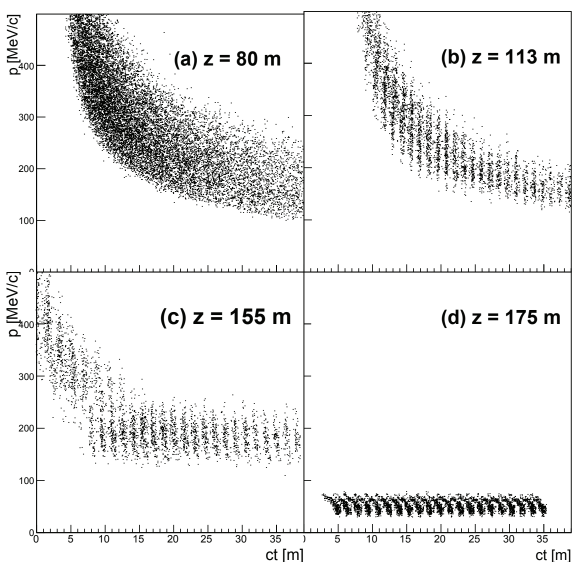

Figure 7: Longitudinal phase space distributions of the muons developing in four stages: (a) Drift, (b) Bunching, (c) Phase-rotation, (d) Deceleration.

After being collected in the magnetic field, the pion beam has a large energy spread which can be reduced to obtain a "bright" muon source for experiments. The pulsed proton driver produces pulsed pion beams, which makes it possible to use rf cavities to deal with the pion/muon beams with large energy spread. The front end concept of a Neutrino Factory/Muon Collider can be applied here.

Figure 7 shows the longitudinal phase space distributions of the muon beam developing in four stages: (a) Drift: the pions drift in a decay channel for 80 m and the muons form a momentum-time correlation. (b) Bunching: a series of rf cavities with frequencies from 233.6 MHz to 319.6 MHz divides the muons into many bunches. (c) Phase-rotation: another 56 rf cavities with frequencies from 202.3 MHz to 230.2 MHz are phased to rotate the bunches in phase space. The high-energy muons are decelerated and the low-energy muons are accelerated to arrive at the same momentum as the reference particle at 160 MeV/c. (d) Decelerate: 25 rf cavities with the same frequency of 202.3 MHz combined with drift sections decelerate the bunches to lower momentum, so that they can be used for various experiment.

Preliminary simulations show that the μ^+ yield at the end of such a four-stage system can reach $4 \times 10^{-4} \mu^+/proton$ with muon momentum lower than 75 MeV/c. With a proton driver power of 500 kW the muon intensity can reach $2 \times 10^{12} \mu^+/s$.

CONCLUSION

We outline a new concept of producing intense muon beams from a spallation target. We collect the surface muons from the upstream surface of the spallation target, and collect the pions from downstream side. We investigate the collecting efficiency with various magnetic settings. Based on the 500 kW CSNS proton driver, the intensities of both the surface muon beam and the pion beam can reach the highest in the world.

The collecting and the compressing systems are still far from being optimized. Further optimization will be done in the future together with consideration of energy deposition and shielding issues.

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