ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-WEPWA021

A NEW DC MUON BEAM LINE AT RCNP, OSAKA UNIVERSITY

Yuki Matsumoto, Akira Sato, Yoshitaka Kuno, Hideyuki Sakamoto,
Yasunori Kohno, Yu Nakazawa, Osaka University, Osaka, Japan
Masaharu Ieiri, Michifumi Minakawa, KEK, Tsukuba, Japan
Hiroshi Ueda, Yoshitaka Kawashima, Keiji Takahisa, Kichiji Hatanaka,
Mitsuhiro Fukuda, Shunpei Morinobu, Osaka University RCNP, Osaka, Japan

Abstract

A new DC muon beam line has been constructed at RCNP, Osaka University. The MuSIC, which has the highest muon production efficiency using superconducting solenoidal magnets, has successfully demonstrated to provide a 3 x 10^8 [μ+/s/μA]. In 2014, the solenoidal magnets of the MuSIC were extended by a new beam line with normal conducting magnets. The new beamline consists of beam slits, quadrupole magnets, bending magnets and a DC separator. This new beamline is designed for muon experiments such as μSR experiments and muonic X-ray measurements. To study the performance of the beams provided by the beamline , a beam test was done in December 2014 and February 2015. In this paper, a detail design of MuSIC including the new beamline and result of the beam test are written.

INTRODUCTION

The MuSIC is a high intensity muon beam facility at RCNP, Osaka University (Figure 1). The proton beam is provided by the RCNP's ring cyclotron. The proton beam power is 400 W. The MuSIC achieves a muon yield of 10^8 [μ+/s/μA]. Compared with that, the the Paul Sherrer Institute (PSI) achieve a same muon yield with 1.3 MW proton beam. This shows that the muon production efficiency of the MuSIC is over 1000 times higher than that of PSI. The MuSIC has two features.

Pion Capture System

The pion capture system is a system involves a pion capture solenoid and a 36∘ curved transport solenoid. Protons enter the pion capture solenoid and hit a graphite target. Pions produced from protons are captured by a magnetic field of the pion capture solenoid and the 36∘ curved transport solenoid transport these pions. Pions decay to muons while transported.

MuSIC M1 Beam Line

MuSIC M1 Beam Line has SLITs(SL), Staring Magnets(STH), Quadrupole Magnets(QM), Bending Magnets(BM) and a DC separator(SR). Particles transported by the 36° curved transport solenoid enter the MuSIC M1 Beam Line. While passing through the beam line, focused muons with uniform momentum are taken out.

PION CAPTURE SYSTEM

The construction of the pion capture system was completed in 2009. In 2010 measurement proved that the Mu-

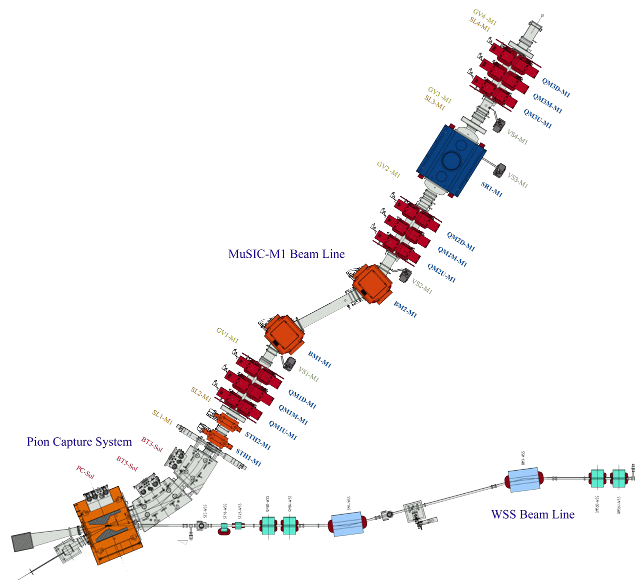

Figure 1: Layout of MuSIC.

SIC achieves about 10^8 [μ/s/μA] muon production efficiency. This is 1000 times higher than that of PSI and TRIUMF. The details are described in this section.

Features

A special structure of the pion capture system is enable the MuSIC to achieve a high muon production efficiency. In the case of the conventional muon beam facility, the neutron facility uses same proton beam line. So the structure of muon beam facility should be like Figure 2 (left. The target is thin and the pion capture solenoid is set beside the target. In contrast, the MuSIC can use full proton beam. Figure 2 (right) shows the structure of the MuSIC pion capture system. A 200 mm thick graphite target stops the protons, so a large mount of pions are produced. Pions are captured by the pion capture solenoid surrounding the graphite target over a large solid angle. It makes pion production and capture efficiency higher. Pions captured by the pion capture solenoid are transported by the 36° curved transport solenoid and decay to muons. A 2 T solenoid magnet and a 0.04 T dipole magnet select muon charge and momentum. Thus the MuSIC obtains a high muon production efficiency.

G4beamline

G4beamline is a simulator based on Geant4 [1]. The MuSIC structure from the graphite target to the 36° curved transport solenoid were described by G4beamline. 392 MeV

ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-WEPWA021

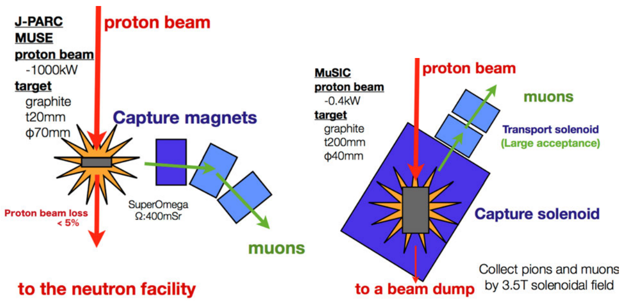

Figure 2: A conventional muon beam facility (left) and the pion capture system of MuSIC (right)..

initial protons were used in G4beamline simulation. The result shows features of muons at the exit of the 36° curved transport solenoid. Figure 3 shows the results of a positive muon flux and momentum distribution when the 36° curved transport solenoid select positive muons. Figure 3 (left) shows the beam size will be about 300 mm Figure 3 (right) shows a peak at 60 MeV/c and the existence of surface muons. Figure 4 shows the results of a negative muon flux and momentum distribution when the 36° curved transport solenoid select negative muons. Figure 4 (left)shows the beam size will be about 300 mm. Figure 4 (right) shows a peak at 60 MeV/c . The new muon beam line was designed based on these results.

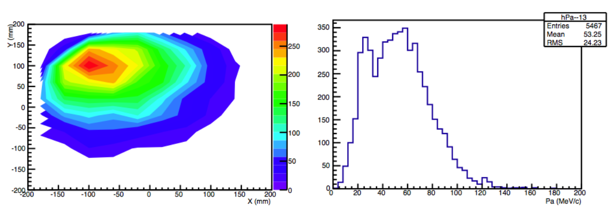
Figure 3: The positive muon flux at the 36° curved transport solenoid (left), and the positive muon momentum distribution at the 36° curved transport solenoid (right).

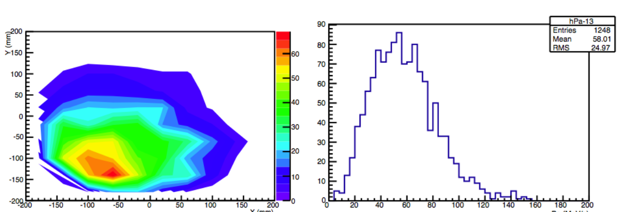
Figure 4: The negative muon flux at the 36° curved transport solenoid (left) and The negative muon momentum distribution at the 36° curved transport solenoid (right).

Measurement of Muon Yield

In 2011 two measurement of a muon yield was done to confirm the performance of the pion capture system. One was measurement of muon lifetime to measure a positive muon yield, second was measurement of muonic X-ray to measure a negative muon yield. A target to stop muons was placed at the exit of the 36° curved transport solenoid and two plastic scintillators (380×50×3.5 mm^3) were placed on either side of the target. Plastic scintillators made triggers and detect electrons decayed from stopping muons for measurement of muon lifetime. And Ge detector was placed to measure muonic X-rays. Table 1 shows predicted values calculated by G4beamline and results of measurements. It indicates that the pion capture system has same performance as designed.

Table 1: The Comparison of G4beamline and Measurement

	Simulation	measurement
μ^+	2×10^8 [μ+/s/μA]	3×10^8 [μ+/s/μA]
μ^-	1.4×10^8 [μ-/s/μA]	$(1.7\pm0.3)\times10^8$ [μ-/s/μA]

MUSIC M1 BEAM LINE

In 2014 the new muon beam line (MuSIC M1 Beam Line) was constructed(Figure 1). In December 2014 and February 2015 a beam test was done. This beam line was designed for measurement of μSR or muonic X-ray. Details of the new beam line is described below using symbols in Figure 1. Particles emitted from the exit of the 36° curved transport solenoid are guided to the beam line by Staring Magnets (STH1, STH2). At that time, emittance of beam is determined by SLITs(SL1, SL2). Each SLITs move x and y axis and cut beam two-dimensionally. Particles passed through SL2 are focused by a Triplet Quadrupole Magnets (QM1). Bending Magnets (BM1, BM2) select momentum of particles passed through QM1. Then particles are focused by a Triplet Quadrupole Magnets (QM2). A DC separator (SR) rotates spin of particles and select muons. A SLIT(SL3) determines the purity of muon and the spread of momentum. At last a Triplet Quadrupole Magnets (QM3) and a SLIT(SL4) determine the beam size.

Beam Line Optics

Transport and TURTLE [2] was used to study the beam optics. The beam profile of the MuSIC M1 Beam Line was calculated by Transport and TURTLE. Figure 5 shows the result of beam profiles. Table 2 shows initial states of the calculation at the exit of the 36° curved transport solenoid. Magnets were set to the setting calculated by the optics.

Table 2: The initial state of the calculation at the exit of the 36° curved transport solenoid. δ depends on gaussian.

δx,δy	$\delta\theta_x$,$\delta\theta_y$	p	δp/p
2 cm	50 mrad	29.8 MeV/c	±3 %

DC Separator

Other names are Spin rotator and Wien filter. DC separator is a feature which rotates spin of particles and selects aimed particles. A voltage and an electric field are applied

ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-WEPWA021

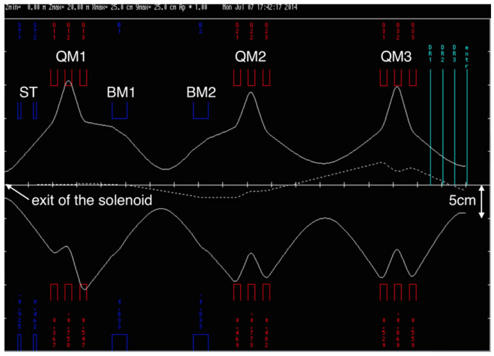

Figure 5: Beam optics calculated by Transport and TURTLE.

at the same time. Charged particles receive Lorentz force (1).

$$\vec{F}_E = q\vec{E}, \vec{F}_B = q\frac{\vec{p}}{m} \times \vec{B} \tag{1}$$

$\vec{F}_B$ bends the trajectry of a charged particle and rotates spin. Momentums of Charged particles which pass through Bending Magnets are same, so $\vec{F}_B$ differe from the mass of charged particles and a heavier particle has longer curvature. This enables to select aimed particle. $\vec{F}_E$ is adjusted to bend thetrajectory of charged particle into original trajectory. In this way, charged particles are selected, and the spin of charged particles are rotated.

Beam Test

A beam test was done in December 2014 and February 2015. A purpose of the beam test is to measure a muon yield. In this paper, only the result of December 2014 is written.

Setup To measure a muon yield, ToF (Time of Flight) measurement was used. A plastic scintillation counter (40 $\times$ 40 $\times$ 1 cm^3) was installed at the exit of MuSIC M1 Beam Line to make a start signal. A proton RF signal was used as a stop signal. RCNP has 16.8 MHz proton beam line. But 16.8 MHz is too fast compared with muon lifetime. So the proton beam was thinned into 1/9 and used as a stop signal.

Analysis Figure 6 shows the result of a ToF measurement. A beam magnets was set to take out 60 MeV/c positive muons. In the ToF data, a faster particle has a larger ToF ch than a slower particle has. So a sharp peak around 2200 ch is a positron peak and a wide peak around 2000 ch is a positive muon peak. There was a flat back ground coused by neutrons. A total number of positive muons was calculated to integrate positive muon peak between red lines with back ground removed. The back ground was calcurated by the average value between the blue line. A muon yield was culculated by (2). A time means a time not except dead time of DAQ. A proton current was measured by a Secondary Emission Chamber (SEC). As a result, a muon yield was 4.2×10^5 [μ+/s/μA].

$$\text{yield } [\mu+/\text{s}/\mu\text{A}] = \frac{\text{total mumber of muons}}{\text{time[s]} \times \text{proton current } [\mu\text{A}]} \tag{2}$$

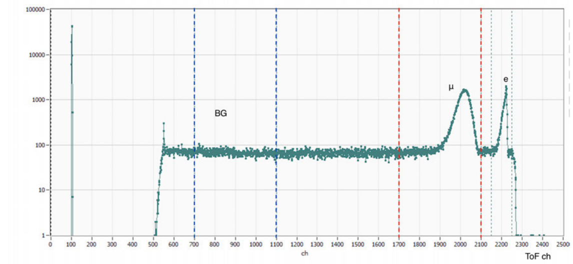

Figure 6: Positive muon 60 MeV/c raw data.

Figure 7 shows a result of positive and negative muon yields for several momentum by changing a setting of magnets. Red points shows the results of positive muons, and blue points shows the results of negative mouons. At this measurement, the DC separator did not work. When the DC separator did not worked, yields of muon and positron whose momentums were 28 MeV/c were 4.3 $\times$ 10^4 [μ+/s/μA] and 1.4 $\times$ 10^5 [e+/s/μA]. When the DC separator worked, yields of muon and positron whose momentums were 28 MeV/c were 6.0 $\times$ 10^4 [μ+/s/μA] and 2.5 $\times$ 10^4 [e+/s/μA]. This indicates that positrons were thinned into about 1/6.

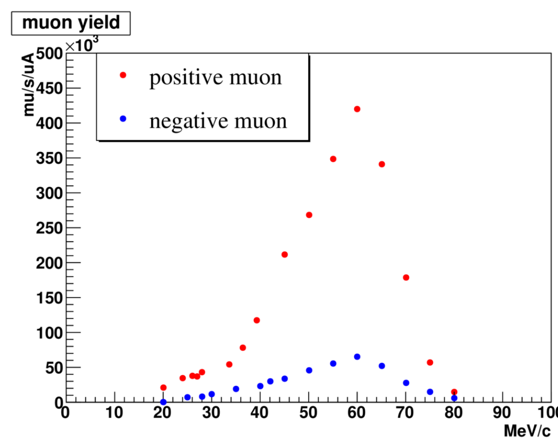

Figure 7: Muon yields for several momentum.

CONCLUSION

The MuSIC is a DC muon beam facility. It has a pion capture system which enable to create muons with high efficiency. According to measurements of muon yield, the pion capture system can provide 3×10^8 [μ+/s/μA] and 1.7×10^8 [μ-/s/μA].

In 2014 MuSIC M1 Beam Line was constructed and in December 2014 and February 2015, a beam test was done. The beam test on December 2014 indicate that MuSIC M1 Beam Line can provide 4.2 $\times10^5$ [μ+/s/μA] when magnets are set to take out 60 MeV/c positive muons.

The result of the beam test on February 2015 still has been analyzed. And in 2015 June, a beam test will be done. At this beam test, we will search muons whose momentum is around 28 MeV/c (surface muons) and measure a beam size.

ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-WEPWA021

REFERENCES

[1] http://G4beamline.muonsinc.com

[2] U. Rohrer, PSI Graphic Transport/Turtle, based on CERN-SLAC-FNAL version by K. Brown et al.

[3] Y. Hino et al,, "A New Intense DC Muon Beam from a Pion Capture Solenoid, MuSIC", Proc. of ICHEP 2012 in Proc. of Science (2013) 550

[4] S. Cook et al., "First Measurements of Muon Production Rate using a Novel Pion Capture System at MuSIC", J. Phys. Conf. Ser. 408 (2013) 012079

[5] T. Ogitsu et al., "New Continuous Muon Beam Line Using a Highly Efficient Pion Capture System at RCNP", TUP020, Proc. of PAC'11 C110328 (2011) 856-858

[6] A. Yamamoto et al, "MuSIC, the World's Highest Intensity DC Muon Beam using a Pion Capture System", MOPZ001, Proc. of IPAC'11 C110904 (2011) 820-822