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Design of the surface muon beamline of MELODY

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Abstract. A Muon station for sciEnce, technoLOgy and inDustrY (MELODY) has been listed in the CSNS upgrade plan. Up to 5Hz of proton pulses will be extracted from the RCS ring to a stand-alone target station. One surface muon will be constructed during CSNS II and another decay muon beamline and more terminals are designed for the future. In this report, we describe the design of the surface muon beamline.

1. Introduction

Muon beams produced with accelerators have applications in many areas of science, including nuclear and particle physics experiments, material science [1], and life science experiments [2]. The China Spallation Neutron Source (CSNS) [3] completed the Phase I project in 2018. The accelerator provides 1.6-GeV 25-Hz-proton beam through the rapid cycling synchrotron (RCS) to hit on the neutron target. At present, CSNS is operating at 100 kW steadily. In the CSNS II upgrade project, the beam power on target will be raised to 500 kW by increasing the average beam current from 62.5 µA to 312.5 µA. A Muon station for sciEnce, technoLOgy and inDustrY (MELODY) is proposed to extend the application of CSNS.

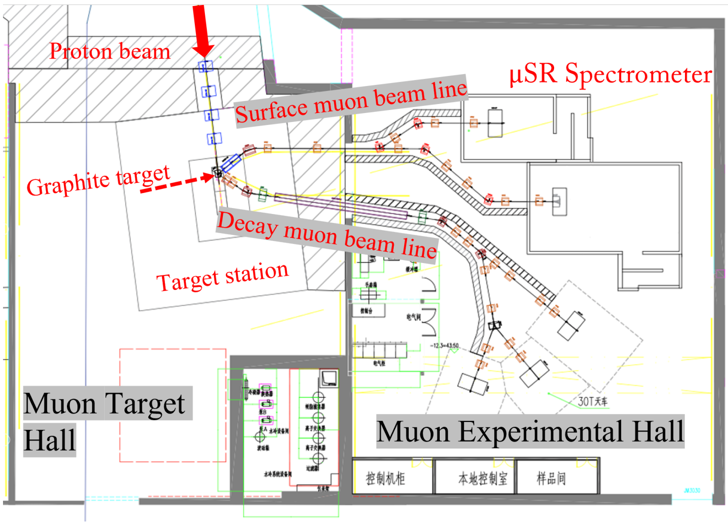

Figure 1. Schematic layout of MELODY. The proton beam was extracted from RCS and transferred to the point of the bombardment at an angle of 7 degrees.

As shown in figure 1, one of the 25 Hz proton pulses will be extracted from the RCS ring to produce muons, and in the future, it could be upgraded up to 5 Hz (100 kW in power). Muons were extracted from the long slab carbon target, and the two beamline deliver surface muons and decay muons to the experimental area. Here we report the conceptual design of the surface beamline, including the target design, the layout and the transport properties of the beamline.

2. Surface μ+ production

In most of the muon facilities, the interaction length and material of the insert-type muon targets are limited due to the requirement of downstream neutron facilities for proton transmission. At MELODY, the stand-alone muon target makes the target length and material adjustable in a wide range. We choose graphite for its relatively high production efficiency and high heat transmission as well as low radiation production compared to high-Z materials. Since the muon experimental hall is on one side of the target station and the other side is the proton application hall, we can only collect the muons from one side of the target. According to the proton beam spot (σ_x=3 mm, σ_y=3 mm), the target with dimensions of 10 cm×10 cm×2 cm is displaced 1σ by the centre of the target, as shown in figure 2(a). After penetrating the muon target, the spent proton beam is delivered to a beam dump. Details of the target station design is described in other proceedings of MuSR2020.

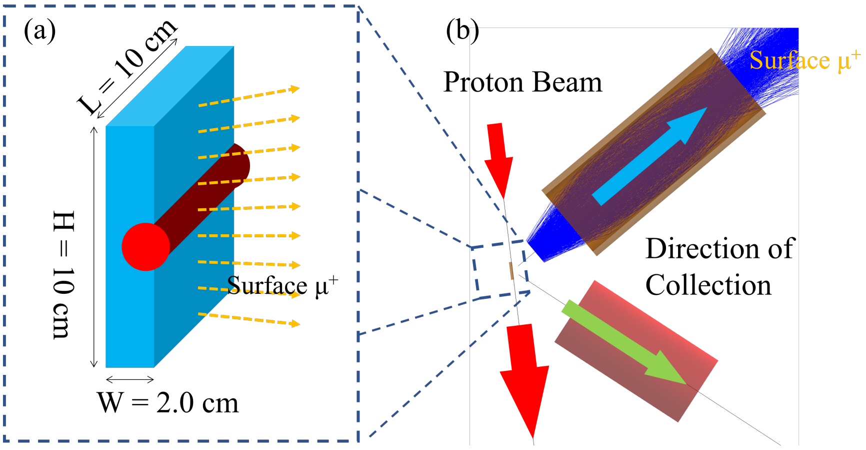

Figure 2. Target area scheme at MELODY. (a) Geometry of the graphite target, and surface muons production. The red cylinder represents the proton beam with corresponding size. (b) Layout of the capture system which delivers muons and pions to different experiment areas.

As shown in figure 2(b), two sets of magnets with large apertures of 400 mm are used to maximize the pion/muon capturing efficiency. For the surface-muon beam, the optimum angle for the capture of surface muons is 90 degrees with respect to the proton beam direction. But due to space constraints, 123 degrees and 50 degrees with respect to the proton beam direction are chosen for surface muon and decay muon respectively. And we collect the surface muons at 0.5 m from the lateral side of the target.

Apart from the parameters of the proton beam and the geometry of the target area, the collection efficiency and the transport efficiency are important for the muon beam quality. Among them, selecting the appropriate emittance and capturing as many muons as possible is the precondition of design. We simulate the muon production and transportation by G4beamline [4]. Figure 3 illustrates the muon distribution in initial phase space at 0.2m from the centre of the proton beam. For distinctive momentum distribution of surface muon, we choose a momentum range from 25MeV/c to 29.8 MeV/c corresponding to the reference momentum of 28.2 MeV/c. Based on the selected phase-space ellipses and the beam emittance of 10879 (horizontal) × 5588 (vertical) π mmmrad as presented, the Courant Snyder parameters (or C-S parameters, listed in table 1) could be calculated using Formula 1.

$$\begin{cases} x_m = \sqrt{\varepsilon_x \bullet \beta_x} = 57.33mm \\ x_m' = \sqrt{\varepsilon_x \bullet \gamma_x} = 250mrad \\ y_m = \sqrt{\varepsilon_y \bullet \beta_y} = 50.32mm \\ y_m' = \sqrt{\varepsilon_y \bullet \gamma_y} = 250mrad \end{cases} \tag{1}$$

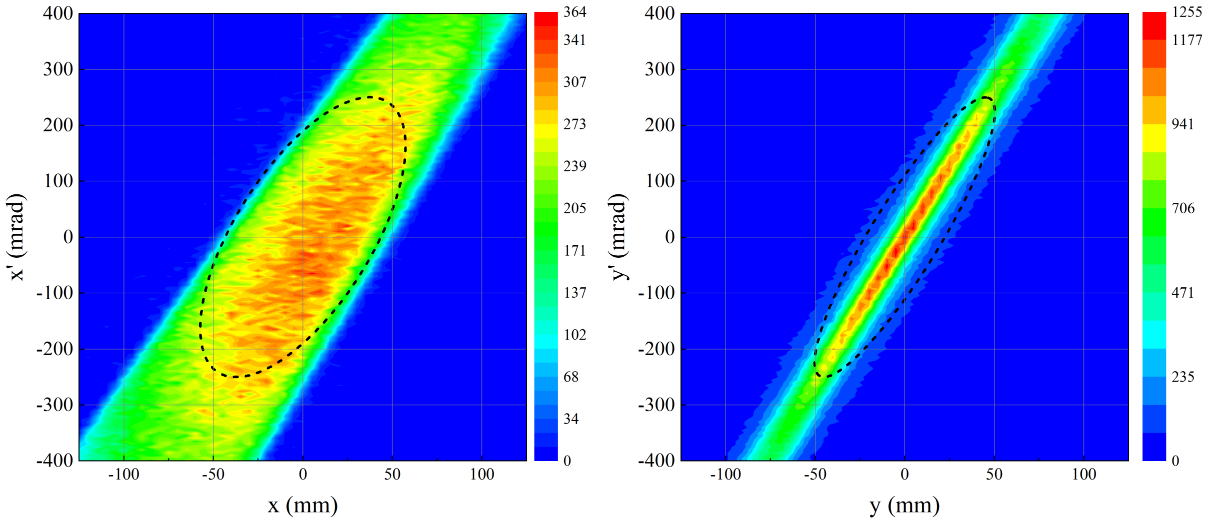

Figure 3. Initial density distributions of surface muons in phase space at 0.2 m from the target. The dashed lines show the emittance ellipses.

Table 1. Initial C–S parameters (at 0.2 m from target).

Muon momentum	$\varepsilon_x\left(\pi\ mm\ mrad\right)$	α_x	β_x	$\varepsilon_y\left(\pi\ mm\ mrad\right)$	α_y	β_y
25-29.8 MeV/c	10879	-0.86	0.3	5588	-2.36	0.59

3. Design of the Surface muon beam line

3.1. Layout and envelope of the surface muon beam line

As shown in figure 4, the 21-meter beam line delivers surface muons from the target into the Experimental Hall by 5 solenoids and 3 dipoles. Following the 1.5-m long capture solenoid, a dipole with a bending angle of 40° was placed to select the required momentum. Two long drifts of 3.1 m and 2.4 m are designed to avoid the blind zone of the crane and install the Wien Filter respectively. Two dipoles with the same bending angle of 34° are used to sweep the neutral particles and filter out the cloud muons. The Wien Filter was employed before the last solenoid to reduce the positron content at the sample.

The gap of the dipole is 200 mm, and solenoids are 500 mm long with three different apertures of 400 mm, 300 mm and 250 mm. As shown in figure 5, the linear optical envelopes of beamlines were calculated starting at 0.2m from the graphite target using graphic transport [5]. The solenoid with a big aperture usually causes the mixing of horizontal and vertical phase spaces and the higher-order effects. The matrix optics is not reliable enough in this case. Based on the parameters from TRANSPORT, the beam line delivers a flux of 1.3×10^7 μ+/s, but the large beam spot of 74mm×54mm FWHM is not suitable for μSR applications. We adapt the Genetic Algorithm in our G4beamline simulation to get a higher flux of muons within the general sample area. The magnet positions and strengths are adjusted in a wide range to search for the optimum beam intensity. We then put two collimators according to the beam envelope to reach a small beam spot. Compared to the TRANSPORT design, the optimized beamline obtains 3.6 times in beam intensity in the area of Ø30 mm. The optimized parameters of the main elements are summarized in table 2.

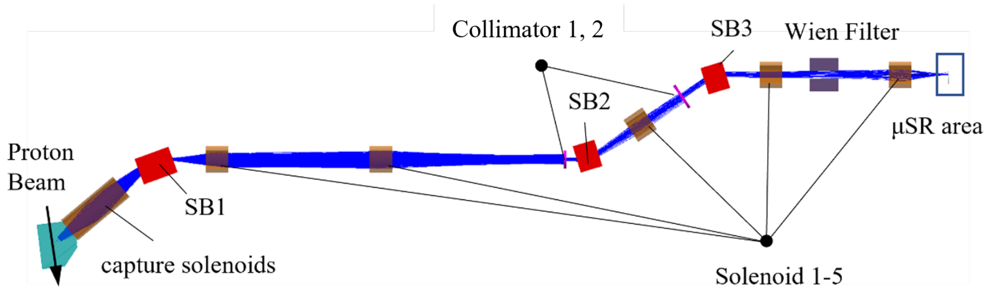

Figure 4. Layout of the surface muon beamline.

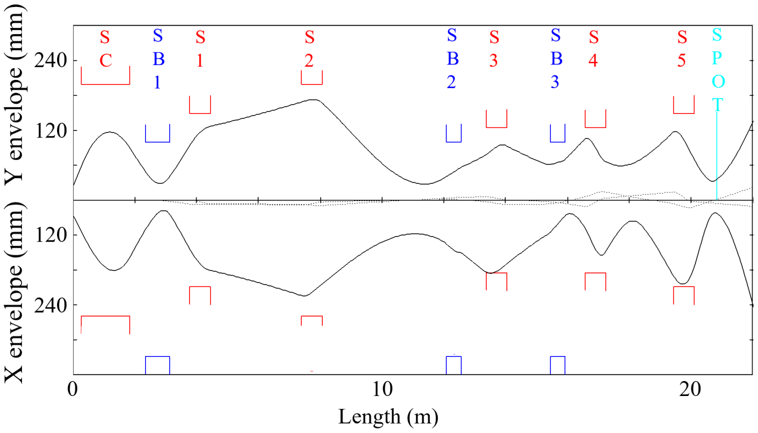

Figure 5. Linear envelope calculated by TRANSPORT.

Table 2. Parameters of the surface muon beamline elements.

	Length (mm)	Effective length (mm)	Aperture (mm)	Field (By or Bz, kG)	Bending angle
SC	1500	1589.79	400	2.25049	
S1	500	685.47	300	2.56947	
S2	500	685.47	400	1.59234	
S3	500	685.47	250	1.97836	
S4	500	685.47	250	0.048253	
S5	500	685.47	300	2.94342	
SB1	796	796	gap = 200	0.8083	40 degrees
SB2, SB3	500	500	gap = 200	1.1	34 degrees
Wien filter	640	800	gap = 180	B_y=214 Gs E_x=1.66 MV/m	$\phi_{e,E} = 185\ mrad$ $\phi_{e,B} = 47\ mrad$

3.2. Removal of positrons

Removing the positron content in the surface muon beam is essential for μSR applications. Positrons in the beam line have similar momenta with surface muons. A Wien filter is placed before the last solenoid to reduce the number of positrons. As indicated in table 2, to keep a reasonable high voltage and avoid sparking, a distance of the separator plates of 180 mm was adopted. The deflection angles can be calculated using an idealized model with homogeneous fields as follows:

$$\begin{cases} \phi_E(mrad) = l_E(m) \bullet \dfrac{E(kV/m)}{\beta p(MeV/c)} \\ \phi_B(mrad) = 30 l_B(m) \bullet \dfrac{B(G)}{p(MeV/c)} \end{cases} \tag{2}$$

with $l_{\mathrm{E,B}}$ effective lengths of E and B-field and ϕ_E and ϕ_B are the deflection angles of the magnetic field and electric field. The total deflection angle ϕ_{total} of a particle is then simply given by

$$\phi_{total} = \phi_B - \phi_E \tag{3}$$

The maximum total deflection angle of $\phi_{total} = 138$ mrad was enough for the separation of e^+ from μ^+, and to avoid severe reduction of the muon beam polarization. Moreover, at the entrance of the down-stream solenoid, as shown in figure 6, there was an additional collimator to block the defected e^+. Finally, the contamination from positron is lower than 1% when the actual flux from the target is transferred, which is simulated by G4Beamline. The simulation shows the Wien Filter removes the positrons with both small beam spot (Ø30 mm) and large beam spot when the collimators are fully open.

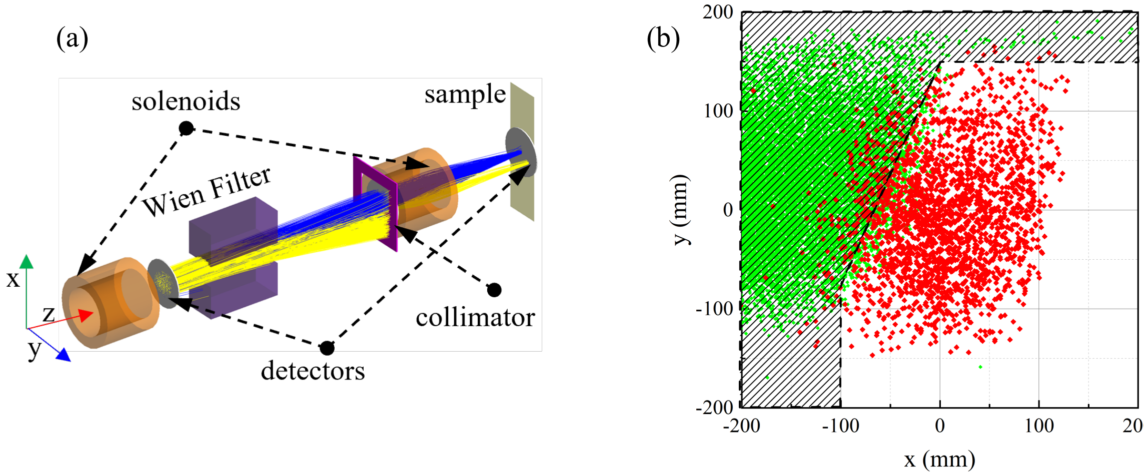

Figure 6. (a) Location and structure of the Wien Filter. The blue tracks represent muon beams, and the yellow tracks represent positron beams. (b)Positron and muon distributions at the entrance of the last solenoid S5 (z=19695 mm), and the shaded part shows the collimator.

4. End-to-end simulation

Following the design above, G4beamline is used to perform the end-to-end simulation to check the performance of the beamline. We use 10^{11} protons to hit the target and the physic model "QGSP_BIC" are used for the whole simulation. Two groups of circular collimators are used to regulate the beam spot size along the z-axis as shown in figure 4.

Muon beam spot and momentum spectrum at the sample are shown in figure 7. The beam has a horizontal size of 1.64 cm and a vertical size of 1.84 cm in Full-Width-Half-Maximum (FWHM). The polarization of the beam is higher than 95% and the momentum spread is about 7% with respect to the reference momentum. Considering 20 kW proton power on muon target, the intensity of the surface muon is around 1.5×10^{6} μ+/s with approximately 90% of muon beam focused on a fixed area size (Ø30 mm). The large single-pulse intensity is useful for increasing the counting rate of the spectrometer and further reducing the beam spot size. The properties are summarized in table 3. Without collimation, we will have an intensity of 1.6×10^{7} μ+/s in a spot area of 33mm×38mm FWHM. In future plans when the repetition reaches up to 5 Hz, we expect the intensity of the surface muon beam line transported to the sample area to be around 8×10^{7} events/s within approximately Ø30 mm in FWHM and the slow muon technology was considered.

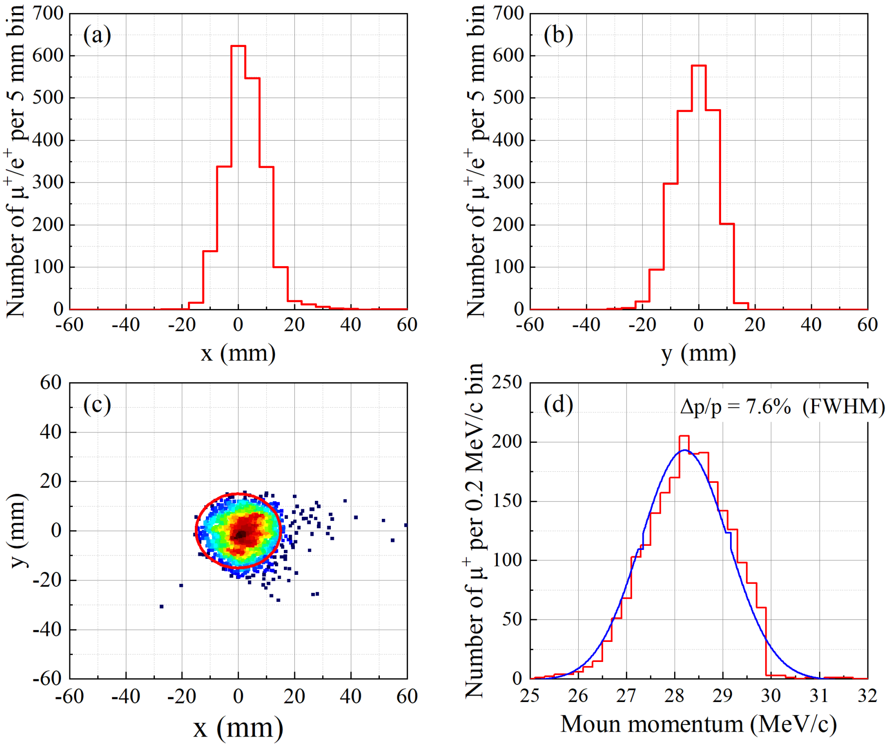

Figure 7. Surface muon beam spot and momentum spectrum at sample place.

Table 3. Parameters of surface muon beam spot at the sample area.

Parameters	Value
Horizontal emittance	2250 πmm mrad
Vertical emittance	1800πmm mrad
x/x' (FWHM)	1.62 cm / 148 mr
y/y' (FWHM)	1.86 cm / 111 mr
Δp/p (FWHM)	~ 7.6%
μ^+ rate	1.68×10^{6} μ^+/s
μ^+ rate on ϕ30 mm	1.53×10^{6} μ^+/s
Core ratio	~ 90%
Polarization	~ 95%
e^+/μ^+	<1%

5. Summary and future aspects

The conceptual design and multi-particle simulations of the surface beamline at MELODY were reported. We use a stand-alone target to produce muons and solenoid magnets to transport them. This scheme maximizes the efficiency of muon yield and transmission for a high-quality muon beam. After the collimation and removing the background positrons, the surface muon flux reaches 1.5×10^6 μ+/s in a beam spot of Ø30 mm. Further work will be carried out to optimize the beam for smaller beam size and lower beam loss.

6. Acknowledgement

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