



Beamline design for multipurpose muon beams at CSNS EMuS

Yang Hong^{1,2,3} · Ying-Peng Song⁴ · Lu-Ping Zhou^{5,6} · Jing-Yu Tang⁷ · Zhi-Hao Zhou^{1,2,3} · Nikolaos Vassilopoulos^{1,2}

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Abstract

A new muon beam facility, called the Experimental Muon Source (EMuS), was proposed for construction at the China Spallation Neutron Source (CSNS). The design of the complex muon beamlines for the EMuS baseline scheme, which is based on superconducting solenoids, superferric dipoles and room-temperature magnets, is presented herein. Various muon beams, including surface muons, decay muons and low energy muons, have been developed for multipurpose applications. The optics design and simulation results of the trunk beamline and branch beamlines are presented. With a proton beam power of 25 kW at a standalone target station that consists of a conical graphite target and high-field superconducting solenoids, the muon beam intensity in the trunk beamline varies from $10^7/s$ for surface muons to $10^{10}/s$ for high-momentum decay muons. And at the endstations, these values vary from $10^5/s$ for surface muons to $10^8/s$ for decay muons.

Keywords Surface muons · Decay muons · Muon beamline · Superconducting solenoids · Multi-channel electrostatic separator

1 Introduction

The study of muons evolved from particle physics and remains an important part in search for physics beyond the standard model, such as the charged lepton flavor violation (CLFV) [1] and the discrepancy of muon $g-2$ [2]. In the

meantime, muons have found widespread applications in multidisciplinary research areas. Interests has concentrated on the use of muons as a very sensitive probe for the microscopic magnetic properties of materials. This is the so-called the μ SR (Muon Spin Relaxation, Rotation, and Resonance) technique [3]. Other important muon applications include the elemental analysis method based on muonic X-ray detection [4, 5], as well as high-momentum muon beam imaging, which is similar to muography, using cosmic muons [6–8].

High-intensity muons are currently available in several world-class laboratories thanks greatly to the development of high-power proton accelerators in the last decades. Globally, there are five muon user facilities for multidisciplinary research: $S_{\mu}S$ at PSI [9], CMMS at TRIUMF [10], ISIS at STFC/RAL [11], MUSE at J-PARC [12] and MuSIC at RCNP [13]. A common goal to upgrade of these muon facilities is to further increase the muon intensity. The most promising method for achieving this goal is utilizing a superconducting capture solenoid around the target, which was first demonstrated at MuSIC [14] and is used in ongoing projects for CLFV experiments, such as Mu2e at Fermilab and COMET at J-PARC [15].

The China Spallation Neutron Source (CSNS) has been in operation since August 2018 [16]. The accelerator complex delivers a proton beam of 1.6 GeV in kinetic energy, 100 kW in beam power and 25 Hz in repetition rate. The upgrading

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✉ Jing-Yu Tang
jytang@ustc.edu.cn

¹ Institute of High Energy Physics, Chinese Academy of Sciences (CAS), Beijing 100049, China

² Spallation Neutron Source Science Center, Dongguan 523803, China

³ University of Chinese Academy of Sciences, Beijing 100049, China

⁴ Radiotherapy Physics and Technology Center, Cancer Center, West China Hospital, Sichuan University, Chengdu 610041, China

⁵ Xi'an Jiaotong University Health Science Center, Xi'an 710049, China

⁶ Department of Radiation Oncology, First Affiliated Hospital of Xi'an Jiaotong University, Xi'an 710049, China

⁷ School of Nuclear Science and Technology, University of Science and Technology of China, Hefei 230027, China

project (CSNS-II), which will start construction in 2023, will boost the beam power to 500 kW by means of higher beam intensity. The Experimental Muon Source (EMuS) was proposed to be constructed at CSNS-II for muon science [17, 18], which will be a standalone pulsed muon facility and uses about 5% (or 25 kW) of the total proton beam power. Two different schemes for the EMuS have been studied, the so-called simplified scheme [19] which was planned to be built first and the baseline scheme as the upgrade. The baseline scheme, which is much more sophisticated, will provide different types of muon beams, as presented herein.

With a long conical graphite target placed in capture superconducting solenoids and forward collection, the EMuS baseline scheme aims to provide highly intense muon beams that are comparable with the existing facilities in some aspects and can be widely applied, such as in μ SR experiments using both surface muons and decay muons, muonic X-ray elemental analysis using negative muons and muon beam imaging using high-momentum muons. These applications were explained in [18] and will be mentioned again in the following sections. However, several challenges in muon beamline systems arise from this novel design, and relevant solutions have been developed.

2 Different muon beams and operation modes at EMuS

2.1 Muon targets and capture systems

Irrespective of particle physics or materials science, a higher muon intensity is helpful for either improving the experimental sensitivity or reducing the time. However, the conventional production targets of muon facilities, such as those at TRIUMF, PSI, ISIS and J-PARC, are located in a field-free region, which result in a low capture efficiency of secondary pions or muons. The efficiency can be notably improved by using an internal target inside a high-field solenoid, which was proposed for a muon collider or neutrino factory in the 1980s [20, 21] and technically demonstrated at the RCNP. At the EMuS, a special design based on a conical graphite target in capture superconducting solenoids and forward collection is employed to provide high-intensity muon beams of quite different characteristics in various working modes with a relatively low proton beam power (25 kW) [22, 23]. The nominal proton beam on the target has a repetition rate of 2.5 Hz and pulse length of approximately 70 ns (FWHM). The decay muon beam will have the same pulse structure, while the surface muon beam will have a prolonged pulse length due to the decay time (26 ns) of the stopping pions in the target. A target with a length of 150 mm, base radius of 45 mm and tip radius of 4 mm, is tilted by 15° with respect to the proton beam to facilitate the

separation between the pion/muon beam and the spent proton beam and increase the polarization of the surface muons. Muons and pions are collected in the forward direction and matched to the trunk beamline. A higher capture field, along with forward collection, is beneficial for collecting energetic pions and decay muons; however, a relatively lower field is preferred for capturing surface muons with a high polarization. Other major factors influencing the target station design include the technical challenges of the high-field large-aperture superconducting solenoids and radiation shielding. The structure of the target station is shown in Fig. 1.

The use of superconducting solenoids causes that quite an amount of cloud muons produced at the proximity of the target are also captured. As these muons have a momentum similar to that of surface muons but a random polarization, the polarization of the surface muon beam is significantly degraded. For example, at the MuSIC beamline, the spin polarization is only approximately 60% [24], whereas at the EMuS, with the efforts such as a 15° tilt angle and a conical target shape, the average polarization of the surface muon beam at the endstations is approximately 70%.

2.2 Layout of beamlines and operation modes

Figure 2 presents the layout of the EMuS muon beamlines. A trunk beamline primarily composed of superconducting solenoids is used to transport muons or mixed pions and muons of a wide momentum range to the muon experimental area. Subsequently, the branch beamlines transport specific muon beams, such as surface muon beams, polarized decay muon beams, negative muon beams, and high-momentum muon beams, to different types of endstations. Various corresponding working modes for the target station and trunk beamline were designed.

In total, eight endstations are planned, and seven of which receive muon beams from the main target station and trunk beamline, as shown in Fig. 2. A thin tandem target upstream

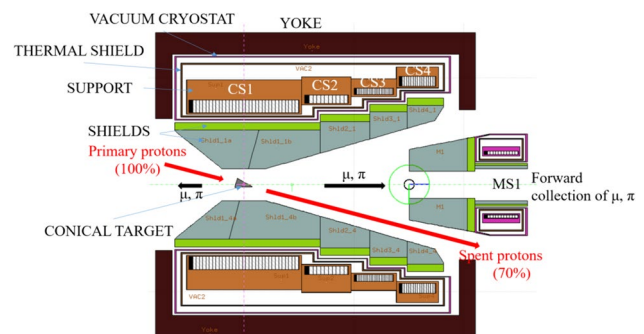


Fig. 1 (Color online) Schematic for the EMuS main target station. CS1–CS4 denote the capture solenoids and MS indicates matching solenoid. The indicated gray and green inner shields are composed of tungsten and B_4C , respectively

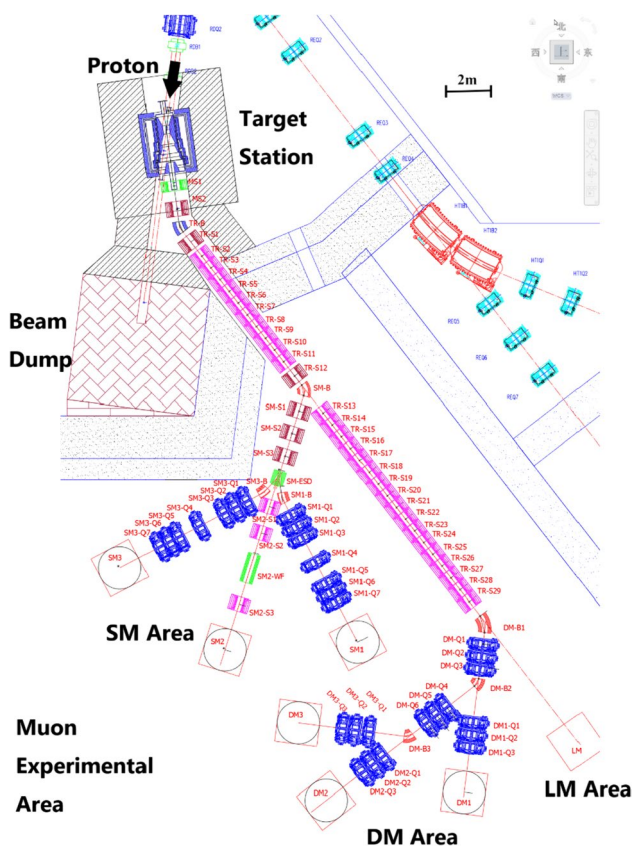


Fig. 2 (Color online) Layout of the muon beamlines

of the main target and a dedicated muon beamline yields surface muons to a μ SR spectrometer in the upper platform, the details of which can be found in Ref. [18]. Figure 2 presents the three muon experimental areas. The surface muon (SM) area provides surface muons for three μ SR spectrometers simultaneously, with the help of a one-to-three electrostatic separator (see Sect. 3.3) using the spatial beam-splitting method. The three experimental setups in the decay muon (DM) area share the beam by utilizing the beam switching modes. These areas serve entirely different types of experiments and use different experimental detector systems with very different muon beams. The low energy muon (LM) area is reserved for future slow muons and potential particle physics experiments. The SM endstations have a normal momentum of about 28 MeV/c for surface muons. For the DM endstations, the maximum momentum is limited to 450 MeV/c for DM1, and 45–150 MeV/c for both DM2 and

DM3. The momentum ranges and species at the endstations are shown in Table 1. This defines a momentum ranging between 28 and 450 MeV/c for the trunk beamline.

Because only one of the three muon species (surface muons, decay muons and low energy muons) are available at a time, different operation modes for the target station and trunk beamline have been designed to optimize the beam properties for various applications. Typically, the optimized capture field is 5 T for high-momentum decay muon beams (muon imaging), 4.4 T for normal decay muons and 1 T for surface muon beams. Certainly, the magnet parameters in the beamlines follow the beam momentum or rigidity.

After the capture solenoids in the target station, two matching solenoids (MS1 and MS2) and one superferric dipole magnet (TR-B) are used to match the collected beam in the phase space between the capture section and transport beamline, and bend it by 30° into the straight section of the trunk beamline, which comprises periodical superconducting solenoids with an aperture diameter of 300 mm in most cases.

The periodical focusing by the solenoids in the trunk beamline is interrupted by a room-temperature dipole SM-B and terminates at the superferric dipole DM-B1. In the surface muon mode, the SM-B deflects surface muons to a branch beamline based on room-temperature solenoids and quadrupoles. In the DM mode, DM-B1 can direct either positive or negative decay muon beams to the branch beamlines in the DM area, where DM1, DM2 and DM3 are arranged clockwise. When switching off both SM-B and DM-B1, the surface muons are directly transported to the LM area, where the muons are moderated for low energy μ SR applications, similar to the LEM at the PSI [25].

The detailed optics designs and performances of these beamlines are presented in the following section.

3 Optics design and simulation results

3.1 Optics design tools and design method

The beam transport in the beamlines is mainly studied by simulations, which are used in iterations to optimize the design of the target station and determine the best performances at the samples of the endstations. The particles produced by the primary proton beam at the target are simulated by the FLUKA code [26] and are used as

Table 1 Endstations and applications in the SM, DM and LM areas

Endstation	SM1/SM2/SM3	DM1	DM2	DM3	LM
Particle	μ^+	μ^+	μ^+	μ^-	μ^+
P (MeV/c)	~ 28	< 450	45–150	45–150	~ 28
Application	μ SR	Imaging	μ SR	Muonic X-ray	Low energy μ

the input to the subsequent beamline simulations in the G4beamline code [27]. G4beamline is well suited for the transport of muon beams with a large emittance and wide spectrum collected from superconducting solenoids. The traditional beamline design software TRANSPORT [28], plays a supporting role in the branch beamline design, where the emittance becomes smaller and comparable to those of typical beamlines.

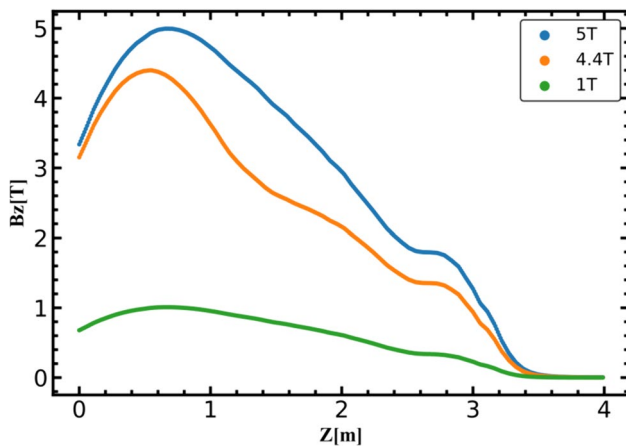


Fig. 3 (Color online) Magnetic field patterns in the target station for different working modes

3.2 Trunk beamline

The trunk beamline starts at MS1 and is mainly composed of superconducting solenoids. For each operation mode, the four capture solenoids and one matching solenoid (MS1) are optimized to collect the pions or muons with different spectrum peaks to ensure a high muon intensity and in most cases, also a high polarization at the destined endstations. Three nominal field patterns in the target station are shown in Fig. 3. Figure 4 presents the momentum spectra of pions and muons at the exit of the MS1. The two peaks at approximately 400 MeV/c and 100 MeV/c in the pion spectrum at 5 T are used for producing high-momentum muons for DM1 and modest momentum muons for DM2 and DM3, while the peak of 260 MeV/c at 4.4 T is for producing intense polarized muons for DM2 or backward decay negative muons for DM3. In the trunk beamline, mixed beams of similar momenta are transported, such as in-decay pions, muons and positrons (or electrons if the beamline is set to transport a beam of negatively charged particles). In traditional quadrupole-based capture systems, positrons are typically several times more intense than surface muons. However, at the EMuS, the solenoid-based capture system collects more positrons and leads to the N_e/N_μ ratio nearly one order of magnitude larger. The removal of positron contamination would be more challenging.

The first section of the trunk beamline matches the beam between the pion-muon capture and the normal beam transport by MS1 and MS2, and performs momentum selection

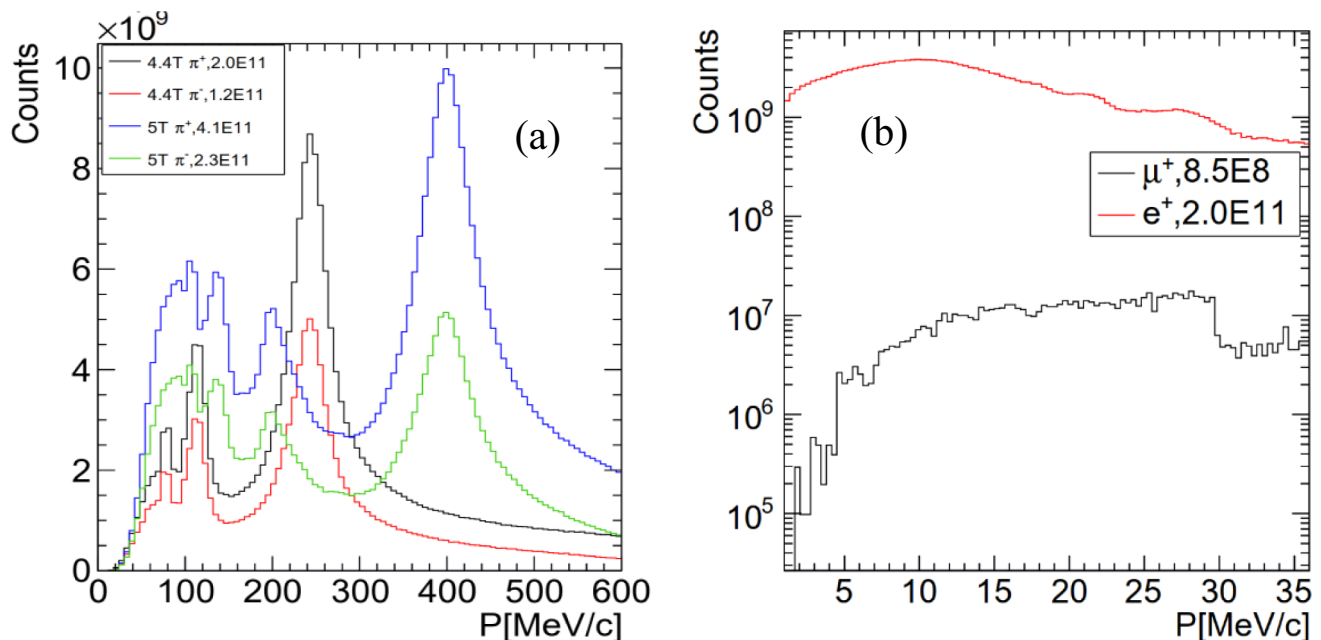


Fig. 4 (Color online) **a** Pion momentum spectra (at 4.4 T and 5 T) and **b** muon/positron momentum spectra (at 1 T) at the exit of MS1. The numbers in the legends indicate the total intensities of the different particle species

by TR-B. To transport different muon beams or hybrid pion-muon beams, the reference momenta of the trunk beamline are adjustable, so are the magnetic fields of the solenoids. To accommodate a beam with a wide momentum and large emittance and provide a bending field of approximately 1.8 T, the TR-B is designed as a superferric dipole magnet [29]. To avoid the complicated coupling of the stray axisymmetric field with the bending field of TR-B, the field shielding yokes of the target station and MS2 are important, and detailed field simulations with ANSYS are used in this section. For the other solenoids, the fields calculated by G4Beamline itself are employed.

For the surface muon mode of EMuS, the only concern for the design of the trunk beamline is the efficient transport of surface muons. Two matching solenoids (TR-S1, TR-S12) and the periodic focusing solenoids from TR-S2 to TR-S11 confine the surface muons before they are bent by 55° into the SM area by the room-temperature dipole, SM-B, which is located at a distance of approximately 14 m from the target. The field pattern and envelope of the surface muons from MS1 to the beam separator (ESD) are shown in Fig. 5. Approximately $1.2 \times 10^8/\text{s}$ muons with a transmission efficiency of 54% reach the SM-B exit, and the transverse RMS emittances simultaneously decrease modestly from $8500 \pi \text{ mm}\cdot\text{mrad}$ to $5000 \pi \text{ mm}\cdot\text{mrad}$.

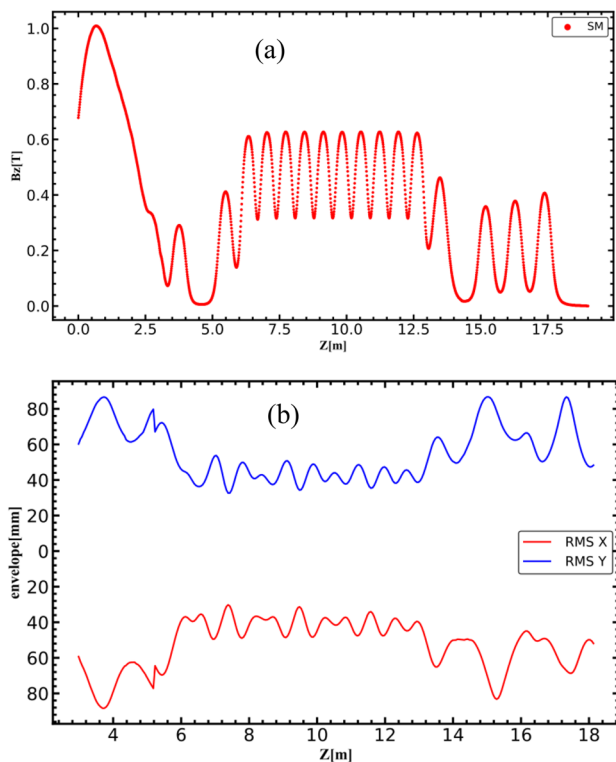


Fig. 5 (Color online) Field pattern (a) and beam envelopes (b) in the beamlines to transport surface muons from MS1 to the ESD in the surface muon area. The calculation is performed by G4beamline

When the EMuS operates in the decay muon mode for experiments at DM1/DM2/DM3, the long straight section of the trunk beamline is significantly useful for allowing most high-energy pions to decay. The momentum of the backward decay muons is significantly different compared to the parent pions, thus they can be well separated by the downstream dipole magnet. This is important for obtaining highly polarized decay muons and for removing the mixed positrons or electrons from the muons. Generally, extremely backward decay muons are selected, and their polarization is higher. Thus, in the straight section, the momenta of pions and muons are significantly different, making it difficult to obtain a high transport efficiency for the mixed beam. At the same time, the periodic focusing in the straight section is disrupted by the switch magnet SM-B. This long drift space is a major site of beam loss, where nearly half of the particles are lost, even the two solenoids (TR-S12 and TR-S13) before and after the break-gap are optimized as matching elements. As shown in the two typical examples in Fig. 6, the second half of the straight section often has lower fields for better transport of decay muons because most of pions decay in the first half. The discontinuity of the beam envelope at certain locations is caused by retaking the statistical analysis of the emittance after the beam loss, and partly because the G4beamline uses three corners to approximate the arc path of a dipole magnet in a piecewise manner. It is the same in the following similar figures.

We adopted a slightly different method for transporting the decay muons with the highest momentum (450 MeV/c) to DM1. Considering that the transverse emittance of the high-momentum beam is significantly smaller than that of the low-momentum beams, as indicated by the simulations, the focusing strengths of the solenoids are reduced to maintain a maximum magnetic field of 3 T instead of scaling with the reference momentum. As the pion momentum needs to be 800 MeV/c to produce extremely backward decay muon with 450 MeV/c momentum, it is unrealistic with current magnets. To obtain a minimum momentum difference of 10% for a clear separation, we increased the pion momentum (defined by TR-B) with a small sacrifice of the intensity, for example, to 550 MeV/c instead of 450 MeV/c to obtain 450-MeV/c muons. Figure 7 presents the field patterns for this case.

The intensities of the different muon beams in the trunk beamline are shown in Table 2; the parameters for the surface muons are obtained at the entrance of SM-B, while the decay muons are analyzed at the entrance of DM-B1. The values in this table indicate the potential for future muon applications, although the present branch beamlines have much smaller acceptance, leading to notably lower intensities at the endstations.

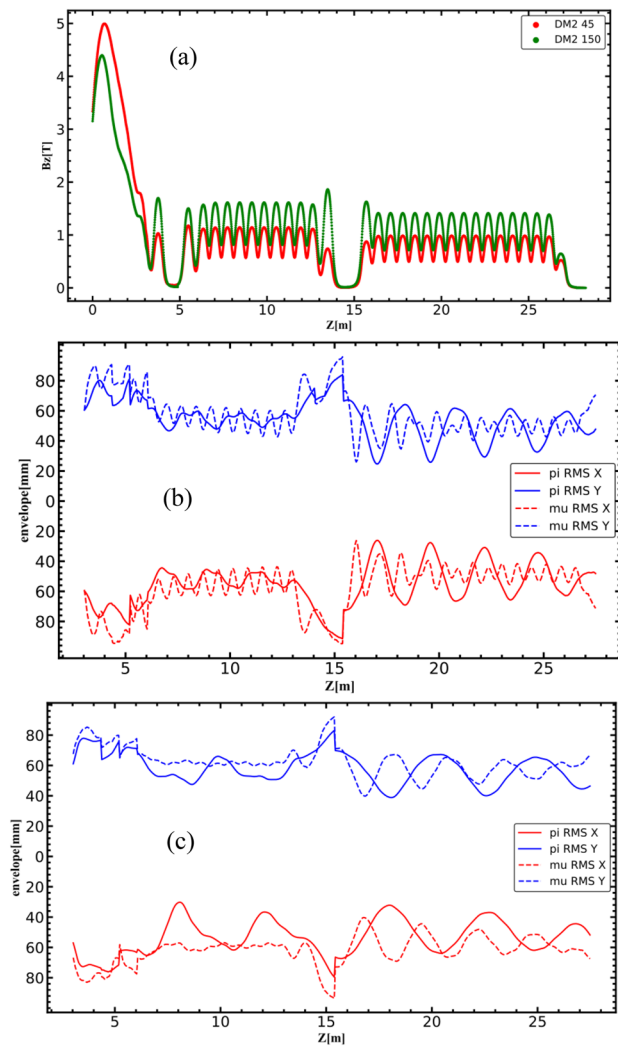


Fig. 6 (Color online) **a** Field patterns in the trunk beamline for transporting the 45-MeV/c and 150-MeV/c muons, **b** envelopes of the 100-MeV/c pions and 45-MeV/c muons, **c** envelopes of the 260-MeV/c pions and 150-MeV/c muons. The calculations were obtained by G4beamline

3.3 Branch beamlines for surface muons

The branch beamline for surface muons starts from SM-B. Three room-temperature solenoids perform the focusing and matching in the phase space for entrance into an electrostatic beam splitter, which is a key element in this design. As mentioned above, a big problem is that the transverse RMS emittances for surface muons remained to be 5000π mm-mrad. The other issue is that the number of contaminating positrons is about 60 times greater than that of muons. Both issues are far beyond the capabilities of traditional muon facilities. Since, μ SR experiments require relatively small beam spots, only beams with small or modest emittances can be focused on the samples. To resolve the aforementioned, a spatial splitting method is employed to split the

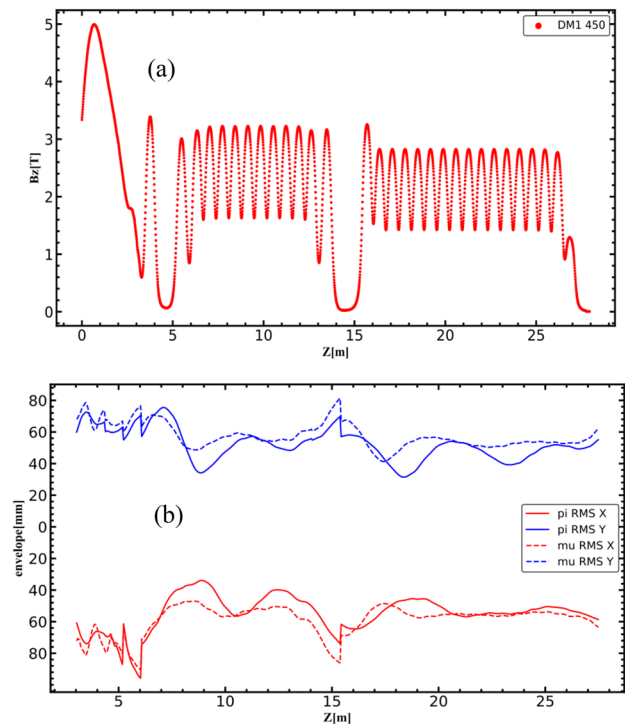


Fig. 7 (Color online) Fields **(a)** and envelopes **(b)** in the trunk beamline for transporting the 450-MeV/c muons. The calculations were performed by G4beamline

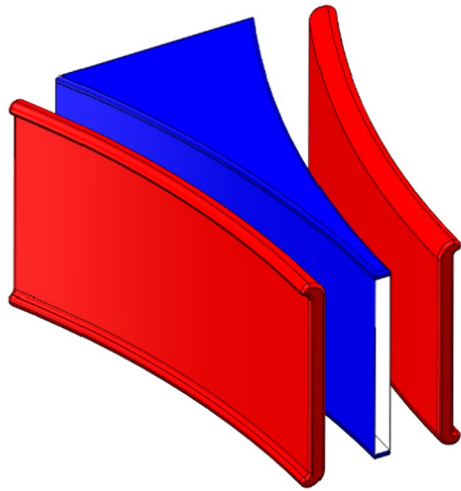
beam into three subbranches for the simultaneous entrance of the beams into the three μ SR spectrometers. The beam-splitting structure consisting of a three-channel electrostatic deflector (ESD) is shown in Fig. 8. Proper matching to the ESD is achieved by the three upstream solenoids to facilitate splitting in the horizontal phase space and focusing in the vertical phase space. The design of the ESD also considers the suppression of positrons owing to the different electrical bending angles of the muons and positrons with the same beam rigidity. A 25° bending angle is selected for the two outer muon sub-beams, resulting in the following set of design parameters: widths of 80 mm, 24 mm and 80 mm for the three gaps, and a voltage of -400 kV applied to the two outer electrodes (shown in red).

3.3.1 SM1/SM3 branch beamlines

A schematic of the three channels after the ESD is shown in Fig. 2. The side channels are installed symmetrically. Excluding the 0.5-m long bending magnet (SM1-B/SM3-B) providing 20° of further bending, the side channels are mainly composed of room-temperature quadrupoles with an aperture of 400 mm in diameter. After the emittance cut in the ESD, the beam in the transverse phase space is no longer elliptical or regular, and the quadrupole arrays require careful alignment. To clean the remaining cloud muons in the

Table 2 Parameters of the muon beams in the trunk beamline

Particle	μ^+			μ^-		
P (MeV/c)	28	450	150	45	150	45
Intensity (s^{-1})	1.0×10^8	6.8×10^9	1.1×10^9	3.4×10^7	6.7×10^8	2.0×10^8
$\Delta p/p$ [FWHM]	5.5%	15.5%	12.4%	13.7%	12.2%	13.6%
RMS emit. (π mm·mrad)	4996/4910	2254/2249	3444/3408	4045/3980	3276/3303	2866/2893
Pol	-0.767	-0.353	0.620	0.793	-0.607	0.115

**Fig. 8** (Color online) One-to-three electrostatic deflector for the SM area. Red indicates the electrodes operating at -400 kV, and blue indicates the earthed central electrode

split beam in SM1/SM3, a 40-mm wide slit after the first quadrupole triplet is applied for further suppression. The rematched optics is shown in Fig. 9. The final polarization

can be increased from 0.65 to 0.76 with this slit, depending on the intensity.

3.3.2 SM2 branch beamline

In SM2, two room-temperature solenoids with an aperture of 300 mm in diameter are used to capture the divergent split beam after the ESD, and another solenoid for focusing the beam onto the sample. As shown in Fig. 10, the positrons in the straight beamline were cleaned to approximately 1% by a dedicated Wien Filter (SM2-WF), which is similar in SM1/SM3. The WF design also benefits from a significantly reduced horizontal emittance. However, considering the overlapping of the surface and cloud muons in the phase space enhanced by the solenoids, the cloud muons cannot be properly removed (Fig. 11). As the results shown in Table 3, the muon beam in SM2 endstation has a much higher intensity but a notably lower polarization than that in SM1/SM3. The beam sizes and intensities at the sample locations need to be adjusted by using a set of slit collimators to meet the requirements for the μ SR experiments, and one example is shown in Fig. 12.

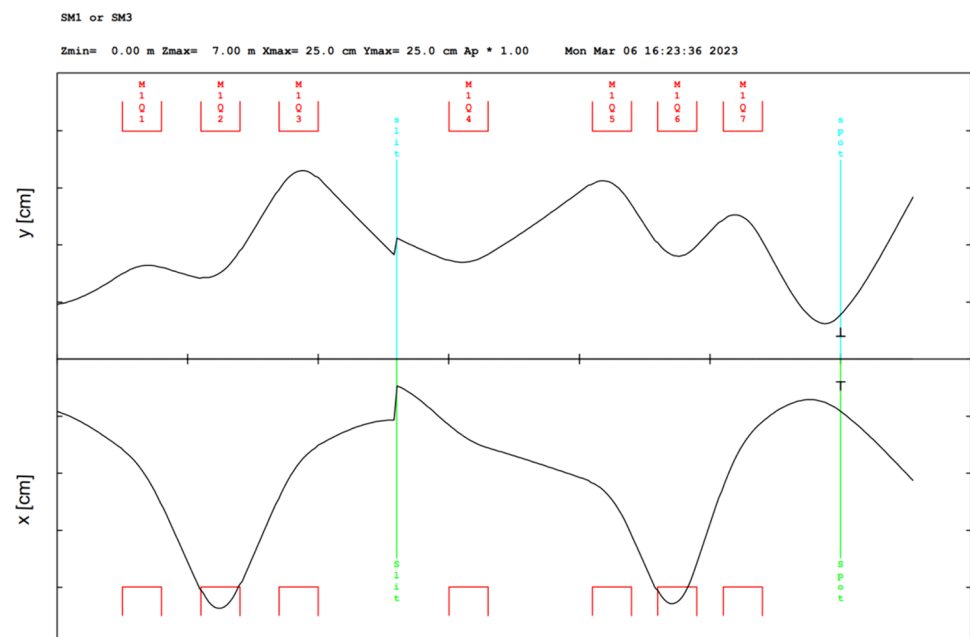
Fig. 9 Envelopes of the surface muon beam from SM1-B/SM3-B to the SM1/SM3 samples. X/Y/Z are the coordinates for the horizontal, vertical and longitudinal directions and the scales are labeled in the upper part of the figure (same for the latter similar figures). The discontinuity at approximately 2.6 m is caused by remaking the emittance statistical analysis for further transport. The calculations are performed by TRANSPORT, so as in the following figures

Fig. 10 Envelopes of the surface muon beam from the ESD to the SM2 sample

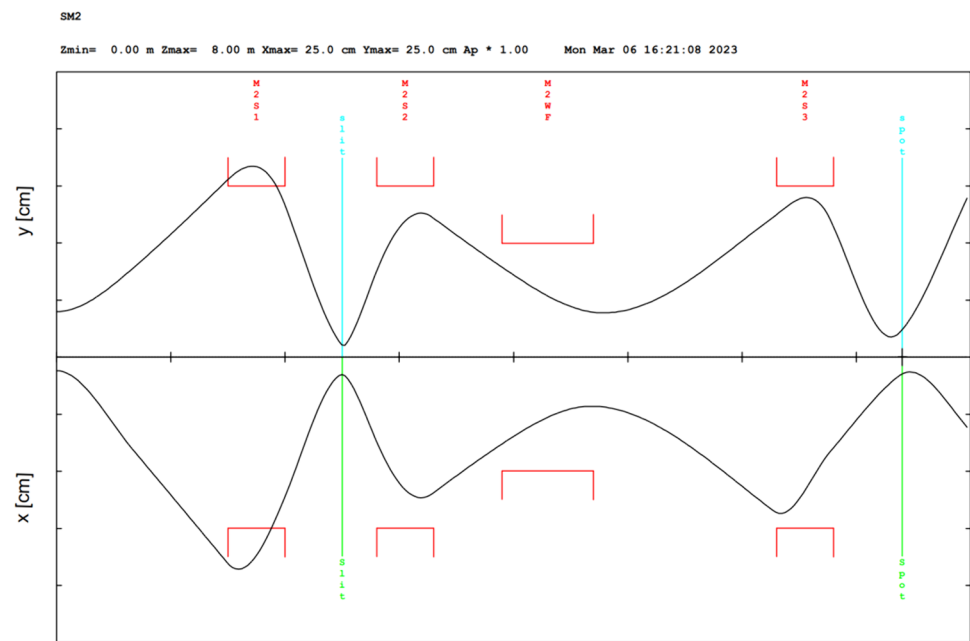


Fig. 11 Envelope of the 450-MeV/c muon beam from the DM-B1 to the DM1 sample position. The solid line inside the beam envelope indicates the dispersion function herein and in the following figures

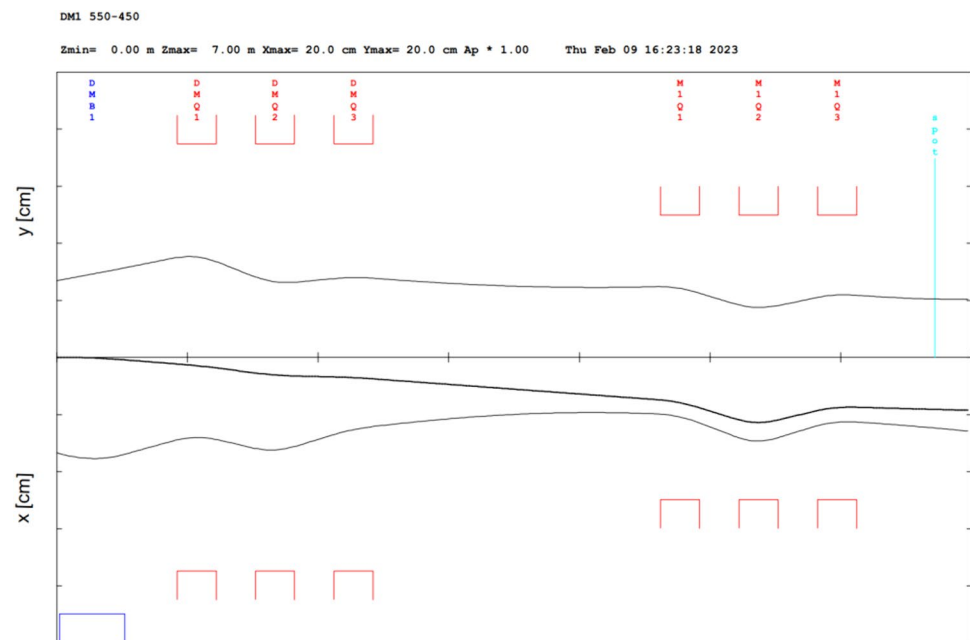


Table 3 Beam parameters for the surface muons at the endstations

Area	SM	LM
Endstation	SM2	SM1 or SM3 LM
Intensity (s^{-1})	2.1×10^6	7.5×10^5 3.9×10^7
Pol	-0.580	-0.760 -0.809
$\Delta p/p$ [FWHM]	9.8%	8.8% 8.7%
Size [X/Y, FWHM, mm]	26.4/30.5	29.2/25.0 69.8/73.3

3.4 Branch beamlines for decay muons

To satisfy the diverse experimental requirements, three experimental setups using decay muon beams are planned in the DM area. The entire beamline system has the ability to provide beams of different momenta and spot sizes, and typical simulation results at the endstations are shown in Table 4. Similar to the surface muon beams, the beam sizes

Fig. 12 Envelope of the 45-MeV/c muon beam from the DM-B1 to the DM2 sample position. The arrows represent positions for the tentative slit collimators to shape the beam spot size and regulate the intensity at the sample position

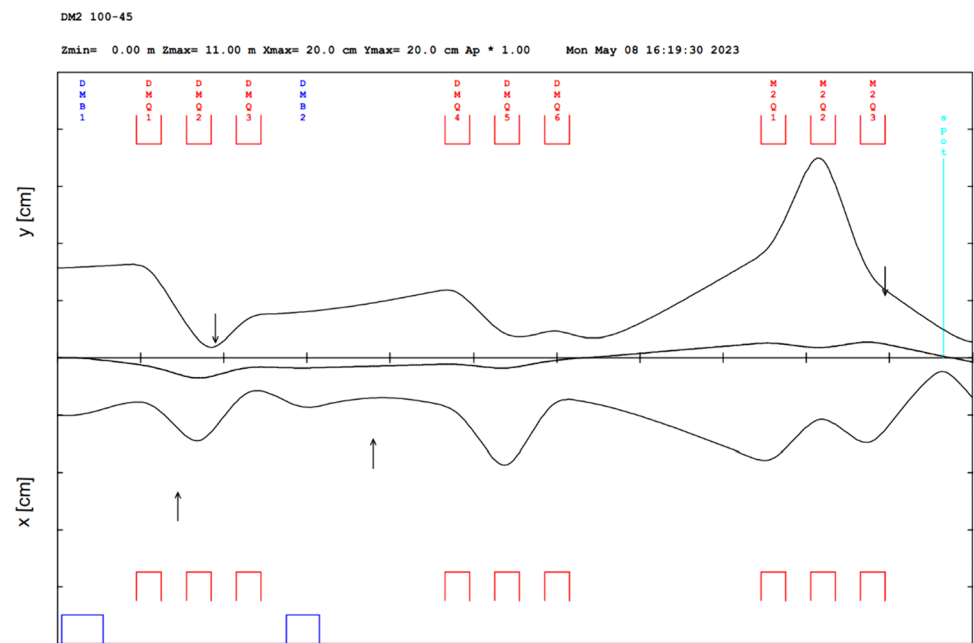


Table 4 Beam parameters at the samples at the three DM endstations

Name	DM1	DM2	DM3
Particle	μ^+	μ^+	μ^-
P (MeV/c)	≤ 450	45–150	45–150
Application	Imaging	μ SR	muonic X-ray
Ref. P (MeV/c)	550/450	260/150	100/45
Intensity (1/s)	5.0×10^8	2.5×10^7	4.2×10^5
Pol	-0.264	0.768	0.846
$\Delta p/p$ [FWHM]	15.3%	9.6%	10.1%
Size [FWHM, mm]	109.7/98.7	29.4/30.3	30.0/29.6

and intensities must be adjusted by slit collimators to meet the experimental requirements. As mentioned earlier, DM1/DM2/DM3 can only work in their dedicated modes and cannot share their beams with others.

3.4.1 DM1 branch beamline

Muon imaging experiments are currently conducted with high-energy cosmic muons up to the GeV energy range [6–8]. The advantage is its high penetrability, such that geometrical objects such as volcanoes can be detected; the drawback is that the measurement time is very long due to very sparse cosmic muons. At EMuS, we plan to develop a novel imaging method using a high-energy muon beam to create images of usual-sized samples at the centimeter scale. DM1 employs muons with momenta as high as 450 MeV/c (equivalent to a kinetic energy of 356 MeV), which corresponds to a penetration length of about 350 mm in iron. As shown in Fig. 4, transportation of a muon beam with a higher momentum and a lower intensity at the start is

possible and would require higher fields for all downstream magnets; however, the overall cost and benefit are not ideal.

Following the muon beam extraction from the trunk beamline by the superferric dipole, room-temperature magnets (quadrupoles and dipoles) are used to transport the high-momentum muon beam to the DM1/DM2/DM3 endstations. For a high-momentum muon beam approaching DM1, the focusing strengths of the quadrupoles become insufficient due to the very large emittance or aperture. We limit the pole-tip field to the usual 0.6 T for the quadrupoles (DM-Q1/Q2/Q3) with an aperture of 300 mm, which means that a relatively weak focusing is applied at 450 MeV/c and a part of the beam is lost. However, the focusing strength is sufficient for transporting a muon beam of 150 MeV/c to DM2 and DM3. For the imaging method using a pulsed muon beam at a repetition rate of a few Hz at the EMuS, the muon intensity from the trunk beamline is considered to be significantly high, which allows us to design a transport system with a relatively low transmission efficiency. In contrast to the

weak focusing at DM-Q1/Q2/Q3, the quadrupoles (DM1-Q1/Q2/Q3) in the subbranch beamline are designed to have a smaller aperture of 200 mm for stronger focusing to produce the required beam spot at the DM1 endstation. While, having these configurations, up to $5 \times 10^8/\text{s}$ muons remains to arrive at the sample with negligible pion or positron contamination. Since, the muon beam imaging technique at DM1 is still under study, the requirements for the muon beam at the sample cannot be completely defined.

3.4.2 DM2 branch beamline

As mentioned earlier, to provide highly polarized decay muons for μSR experiments at DM2, backward decay muons instead of forward decay muons are chosen for their larger momentum separation from the parent pions. The muon momentum range of 45–150 MeV/ c can be easily covered by varying the settings of the trunk beamline and branch beamlines, particularly TR-B and DM-B1. After DM-B1, the transport of the transverse phase spaces becomes decoupled in linear optics. Therefore, an achromatic mode can be designed for the sample in principle; however, the non-achromatic optics shown in Fig. 12 is adopted to obtain a reasonable spot size with a greater intensity. Two of the slits are for the x -direction and momentum collimation, and the other two are for the size in the y -direction. They can improve the momentum resolution to several percentage (FWHM) and control the spot size at the sample ranging between $\Phi 10$ mm and $\Phi 30$ mm (FWHM).

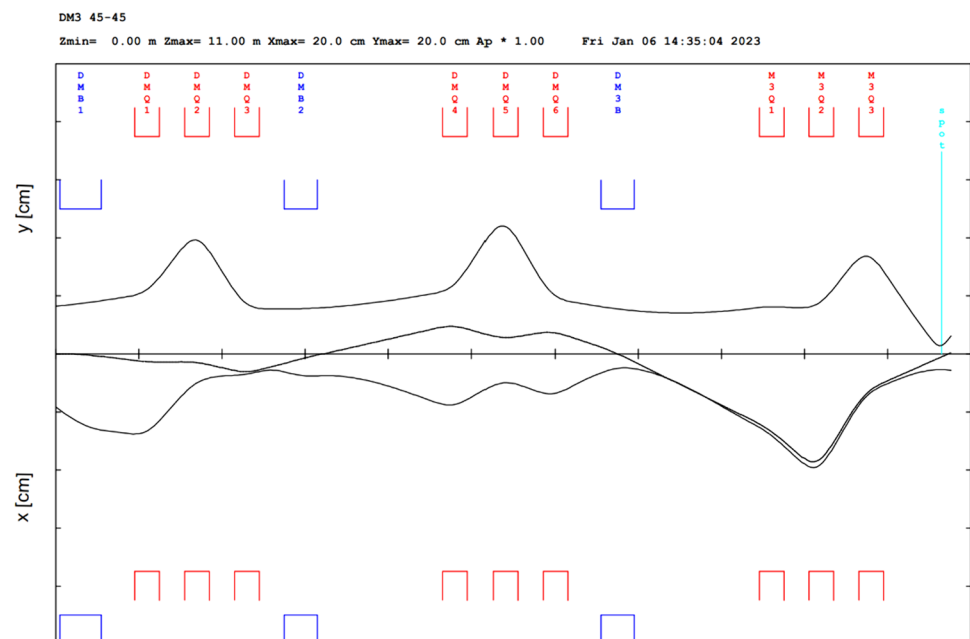
3.4.3 DM3 branch beamline

Because muon polarization is not required for muonic X-ray experiments, the operation mode for DM3 can be more flexible. There are two options for providing negative muons at DM3. With backward decay muons similar to those at DM2, the intensity can be at least $2 \times 10^5/\text{s}$ muons, which increases with the momentum in the 45–150 MeV/ c range and may be sufficient for regular experiments. For low-momentum (e.g., 45–60 MeV/ c) muons, cloud negative muons generated at the proximity of the target are an alternative option, which can provide an intensity nearly one order of magnitude greater. The optics used to transport these cloud muons is shown in Fig. 13. However, in this case, it is difficult to prevent electron contamination and may not be acceptable for the experimental system. Electrons introduce an X-ray or gamma ray background via the bremsstrahlung effect. A study for reducing the bremsstrahlung background by arranging the X/ γ detectors away from the forward direction is underway, because bremsstrahlung is strongly forward directed.

3.5 Low energy muons

The only operational low energy (eV-keV) muon beamline is currently at PSI/LEM [25]. Meanwhile, the method of applying the laser ionization of muoniums to produce extremely low energy muons is under testing or development at ISIS and J-PARC/MUSE [30]. There are other promising methods for muon moderation such as frictional cooling using helium gas [31] and muCool [32]. At EMuS, we plan to produce low energy muons based on the LEM method using

Fig. 13 Beam envelope of the 45-MeV/ c cloud muon beam from DM-B1 to the DM2 sample position



solid Neon or Argon as a moderator. To support this type of experiment, a dedicated endstation (LM) for low energy muons is reserved at the end of the trunk beamline. When surface muons are delivered to the end of the long straight section for the LM area rather than the SM area, the fields from TR-S13 to TR-S29 are similar to those of TR-S2 to TR-S11. After the drift in DM-B1, a room-temperature solenoid is used to focus surface muons onto the moderator. Due to the disruption of the periodic focusing at SM-B and DM-B1, the maximum muon intensity on a spot size of 70 mm $\times$ 73 mm (FWHM) at the moderator is estimated to be about $3.9 \times 10^7/\text{s}$ (see Table 3). If the dipoles are replaced by solenoids in a movable mode, the muon intensity would be higher than $1 \times 10^8/\text{s}$. A low energy beamline and an experimental system similar to the LEM can be considered. Another experiment is also under investigation, such as the muonium to anti-muonium conversion experiment (MACE) by employing high-intensity surface muons in this area [33].

3.6 Mixed beams in the beamlines

For the surface muon beams to the SM endstations, positron contamination can be suppressed to less than a few percent with ESD and SM2-WF. In most cases, by using backward decay muons at DM1/DM2/DM3, positrons (or electrons) and nondecayed pions are removed to a negligible level by DM-B1. However, the pion loss along the channel due to poor transmission, especially when serving very high-momentum muons at DM1, would present problems for the radiation shielding of the experimental area because they would generate almost the same order of neutrons and gamma rays, mostly in the energy range of 1–10 MeV. The shielding walls along the trunk beamline are considered to form a removable tunnel to maintain the remaining of the experimental hall and all endstations at a low level of radiation. For the transport of surface muons to LM, there is no applicable mechanism for removing positrons before DM-B1. Considering that an electrostatic mirror and a spin rotator are installed after the moderation target, separating the positrons and muons by the mirror and spin rotator is relatively easy. No Wien Filter is currently planned before reaching the moderation target. However, the long-term stability of the moderator under very high flux of relativistic positrons remains unknown and should be considered in the future.

4 Conclusions and discussions

In conclusion, the design of EMuS baseline offers various muon beams of high competence for different applications. This optics design, including the addressing of other physical issues, is presented herein. The trunk beamline transports or

produces high-intensity and high polarization surface muon beams of about 28 MeV/ c , decay muon beams of 45–150 MeV/ c , high-intensity negative muons of 45–150 MeV/ c , and high-momentum muon beam of up to 450 MeV/ c . It is based on the focusing of superconducting solenoids to tackle with the extremely large transverse emittance and momentum bite, as well as the very different working modes. The branch beamlines transport the muon beams to the endstations with the required properties, which include the beam size, momentum bite, and suppression level of contamination by other particles. The design is mainly accomplished through simulations with G4beamline, though TRANSPORT is also used to demonstrate the envelopes in the branch beamlines. Targeted solutions for typical problems, such as the exploitation of extremely large emittance beams, high positron contamination, and very high-momentum muons, have been developed.

Due to the significantly low repetition rate at EMuS, which is notably different from that of other pulsed muon facilities, relevant experimental methods for muonic X-ray elemental analysis remain under development. As regards muon beam imaging using high-momentum muons, no existing experimental method serves as a direct reference, for which dedicated efforts are being made. Thus, the beam transport and delivery system retain a large capacity to be modified to follow the future requirements of experimental methods for muonic X-ray elemental analysis and muon beam imaging.

Although a different design—with similarities to the EMuS simplified scheme—will be constructed at CSNS, the EMuS baseline scheme can serve as a good reference for future muon facilities with a standalone target.

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Data availability The data that support the findings of this study are openly available in Science Data Bank at <https://cstr.cn/31253.11/sciencedb.j00186.00128> and <https://doi.org/10.57760/sciencedb.j00186.00128>.

Declarations

Conflict of interest The authors declare that they have no competing interests.

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