Progress report on Muon Source Project at CSNS

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Abstract. A Muon station for sciEnce, technoLOgy and inDustrY (MELODY) has been listed in the China Spallation Neutron Source upgrade plan, and the infrastructure construction is scheduled to start by the end of 2022. The 1.6 GeV double-pulsed proton bunch will be extracted from the Rapid Cycling Synchrotron (RCS) ring to a stand-alone target station. One surface muon and one decay muon beamline are designed to provide multi-terminals for applications. In this report, we describe the design of MELODY and prospect for future applications.

1. Introduction

Muon beams have been used in various applications including particle physics [1] and material research [2]. In China, we have designed a Muon station for sciEnce, technoLOgy and inDustrY (MELODY) based on China Spallation Neutron Source (CSNS)[3]. The project will be constructed during the Phase II upgrade of CSNS. As a start-up project, we will build one surface muon beamline with one μSR spectrometer and leave the decay muon beamline and more terminals for the future. Here we briefly introduce the CSNS facility and report the progress of the design and technique development of MELODY. The detailed design of the target station, the surface muon beamline, the spectrometer and the beam measurement are presented in other proceedings of the 15th International Conference on Muon Spin Rotation, Relaxation and Resonance.

2. CSNS and MELODY

The layout of CSNS is shown in figure. 1. The linac accelerates the H^- ions to 80 MeV (will be upgraded to 300 MeV in CSNS II) and two electrons are stripped off before the protons are injected into the Rapid Cycling Synchrotron (RCS). The proton bunches are accelerated to 1.6 GeV in the ring and extracted to hit the neutron target at a repetition rate of 25 Hz. The proton power is currently 100 kW and will be upgraded to 500 kW in CSNS II.

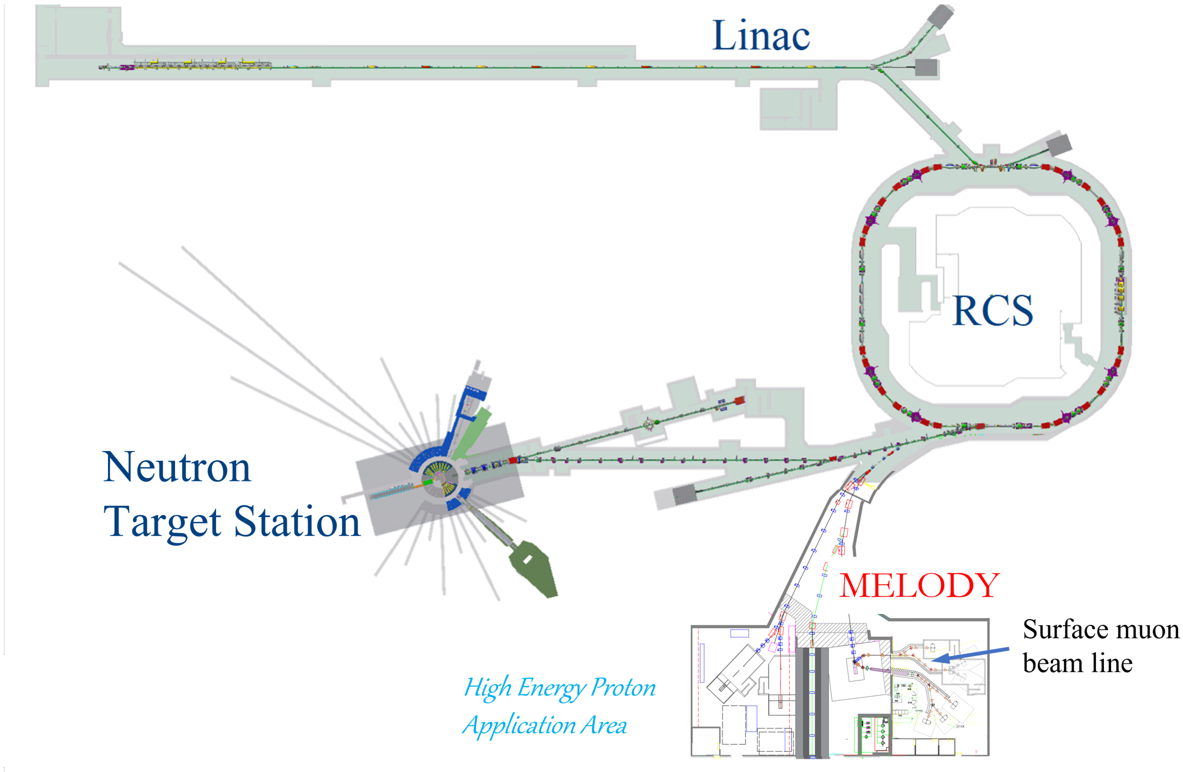

Figure 1. Schematic layout of MELODY.

Spallation neutron facilities with muon sources such as ISIS and J-PARC use insert targets to produce muons. This maximize the utility of the proton beam. Feasibility studies of several similar schemes at CSNS were carried out, but it turned out that the current space was limited for muon beams and it might bring risks to the exist tunnel structure. So, to produce muons, we extract the protons from the RCS ring to an empty space. The proton pulse has a double-bunch structure with around 150 ns bunch width and a separation of 410 ns. The 1.6 GeV proton hits on a carbon target with an interaction length of 12 cm. The spent beam is absorbed by a beam dump. We designed two beamlines for surface muon and decay muon applications. The surface muons from the target are collected by a couple of large aperture solenoids and the pions will be guided by quadrupole triplets and superconducting solenoids. Here we mainly focus on the surface muon beamline which will be built in the CSNS II project. The surface muon beamline is a full solenoid beamline to reach large acceptance with lower cost. The beamline delivers 1.5×10^6 μ^+/s with a full spot size of ϕ3 cm at the sample. Since the repetition is low (1 Hz to start and could reach up to 5 Hz in the future) and the single-pulse intensity is high, we designed a spectrometer with large number of detectors for muon spin rotation/relaxation/resonance (μSR) applications. Following we describe the design of the target station, the surface muon beamline, the spectrometer and the beam measurement respectively.

3. Target station

Figure 2 shows the schematic layout of the target station. After passing through a thin beam window, the protons hit on a carbon target, which sits inside a vacuum vessel. We collect the surface muons and pions from the same side of the target, and the two beamlines are 123° and 50° to the proton beam respectively. The three layers of shielding blocks are used to reduce the radiation dose to lower than 2.5 μSv. The first layer of shielding is graphite with 0.4 m thick

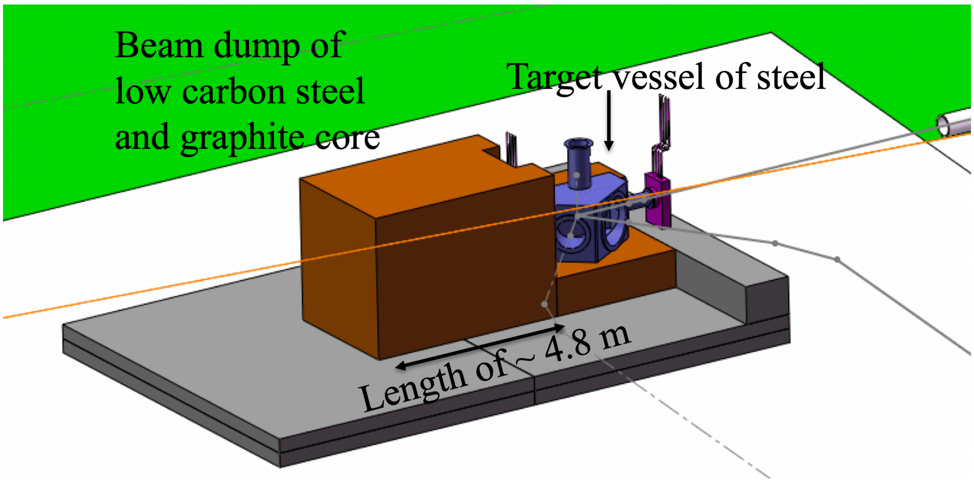

Figure 2. Schematic layout of the target station.

on the side and 2.8 m thick downstream to absorb most of the spent protons and produce less radiation. Then on the side we use 2 m thick mild steel and 5 m thick concrete for shielding and downstream we have 4.8 m steel and 4.5 m concrete.

Since we only collect the pions/muons from one side of the target, we adopt a semi-interaction strategy to maximize the muon production. The center of the gaussian-distributed proton beam is 1σ (the standard deviation of the beam spot in horizontal direction) off from the surface of the rectangular target. With this setting, we gain about 20% of the surface muon rate within an emittance of 5000 πmmmrad, comparing to a beam centered target. We optimize the target geometry with FLUKA [4] and G4beamline [5] Bertini model. The G4beamline simulation predicts about 2.2 times more surface muons than FLUKA. Further work are needed to cross-check with other muon facilities.

4. Surface muon beamline

We collect the surface muons from the backward direction for fewer cloud muon, and collect high energy pions from forward direction for higher energy and flux. Here we describe the surface muon beamline design. Traditional muon beamlines are built with quadrupole magnets because they have stronger focusing fields than those of solenoids. However, surface muon beam has a low momentum of 28 MeV/c, so solenoid magnets are strong enough to focus the beam. Hence we use solenoids to collect and transport the surface muons for relatively lower cost and larger acceptance compared to those of quadrupole triplets.

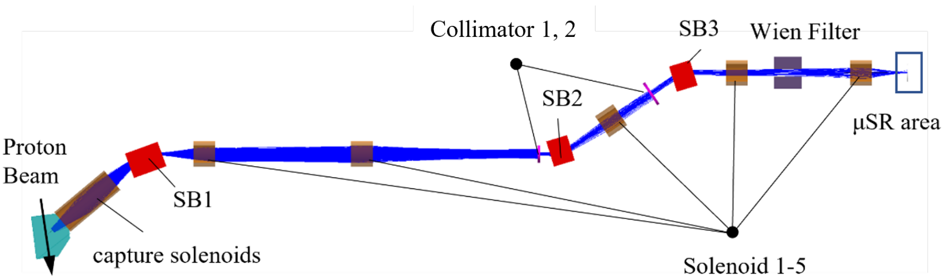

Figure 3. Surface muon beamline simulated with G4beamline.

As shown in figure 3, we first use a couple of large aperture solenoids to collect the surface muons and focus the beam to get through the bending dipole magnet (SB1). Then another pair of solenoids (Solenoid 1 and 2) are used to match the beam to the next bending section. The long straight section between Solenoid1 and SB2 is designed to avoid the blind zone of the crane in the target hall and experiment hall. Two more bending sections are designed to further reduce the momentum spread and deliver the muons to the μSR area. A Wien filter is used to remove the positrons in the beam. The sample is at a distance of 0.8 m to the last solenoid. Reduction of the fringe field of the last solenoid is under investigation. Because the mixing of horizontal and vertical phase spaces by solenoids, we use two sets of circular collimators to reduce the beam size at sample position.

We simulate the beamline with G4bealine, using 10^{11} protons on target. The final beam spot at the sample position is 1.64 cm×1.84 cm (FWHM), with 90% muons in a ϕ3 cm area. The polarization of the beam is higher than 95% and momentum spread about 7% in FWHM. With 20 kW proton power we achieve a surface muon intensity of $1.8 \times 10^6 \mu^+$/s from simulation. Without collimation the intensity could reach $1.6 \times 10^7 \mu^+$/s with a spot size of $33 * 38mm^2$ FWHM. Such a high intensity beam could be used to produce a slow muon beam when a high efficiency moderation technique is available. We are developing a muon cooling technique based on frictional cooling method and we expect to reach an efficiency of 10^{-4} to produce slow muons from a surface muon beam.

Table. 1 lists the beam parameters. Based on the physical design we have been carrying out engineering studies for the beamline elements such as the radiation-hard magnets and the Wien filter.

Table 1. Design parameters of the surface muon beam.

Parameters	Value
Horizontal emittance	2250 π mm mrad
Vertical emittance	1800 π mm mrad
x/x'(FWHM)	1.62 cm/148 mrad
y/y'(FWHM)	1.86 cm/111 mrad
Δp/p(FWHM)	7.6%
Polarization	95%
μ^+ rate on ϕ30mm	$1.6 \times 10^5 \mu^+/s$
e^+/μ^+	1%

We leave the space for the other decay muon beamline and more terminals for the future. The high-energy pions will be collected by quadrupoles and decay in a long superconducting solenoid. Muons up to 300 MeV can be collected and transported to terminals and various applications can be carried out at different energies.

5. Spectrometer

We will construct one μSR spectrometer during the CSNS II project. Because the muon beam repetition rate is low and the single pulse intensity is high, we design the spectrometer with large number of detectors in order to have an appropriate data counting rate. On the other hand, the high single-pulse intensity can also be used to increase the asymmetry of the spectrometer by using thick degraders.

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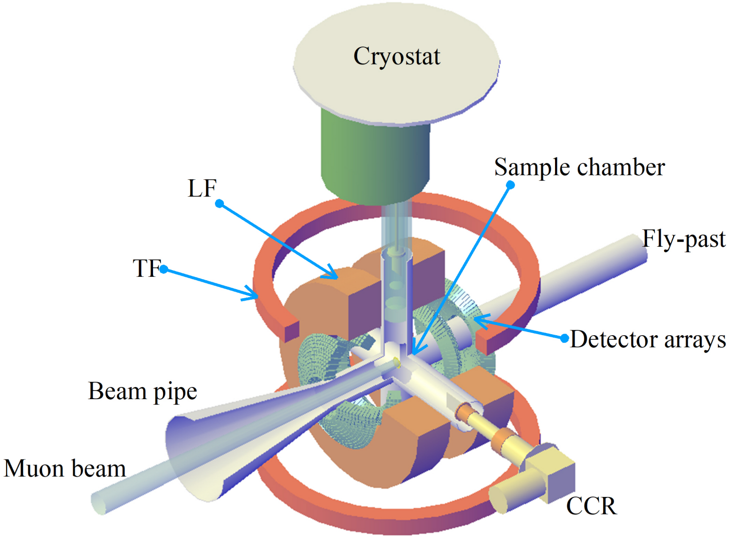

Figure 4. Schematic layout of the μSR spectrometer.

Figure 4 shows the schematic layout of the spectrometer. We use plastic scintillators with fast SiPMs as positron detector units. They are spherically arranged and pointing to the center of the sample, covering 54% of full sphere. Each unit has a single-channel count rate of about 8 e^+/ch/pulse. With 2800 units we reach a counting rate of 80 MEvents/h and the asymmetry of the spectrometer is above 0.28.

The sample environment includes the cryogenic systems and magnetic fields. A Close-Cycle Refrigerator (CCR) will be provided to cover a temperature range from 10 K to 600 K. The CCR is installed horizontally through the vacuum chamber. A cryostat installed from the top of the sample chamber will provide a temperature down to 2 K and with a low temperature plug-in we can reach 300 mK in the future.

Longitudinal and transverse magnetic fields are provided by two sets of solenoids. The longitudinal field reaches up to 0.5 T, so a pair of high-power water-cooled solenoids are designed with a field homogeneity of 100 ppm at sample area. The transverse field of the spectrometer is designed to go up to 400 G to best fit the muon pulse width. The geomagnetic and ambient fields must be offset to obtain a zero-field sample environment. We designed three pairs of compensating coils and the accuracy is better than 1 mG. The last solenoid on the beamline will be magnetically shielded to limit the fringe field at the sample lower than geomagnetic field.

6. Beam measurement

An intensity measurement for the pulsed muon source together with positron discrimination is proposed. A double-stacked scintillator detector scheme with photomultiplier tube (PMT) and waveform-sampling readout electronics is designed to measure both the muon intensity and fraction of positrons (figure 5). The muons will be stopped by the first scintillator and the positrons in the beam will pass through and deposit energies in both scintillators. From the scintillators we measure the deposit energy and then we calculate the number of particles correspondingly. In Scint1 we can calculate the muon beam intensity by extrapolate the decay positron spectrum and subtract it from the whole energy spectrum, and from Scint2 we can get the content of the positrons in the surface muon beam.

We simulate this detection scheme with Geant4. We use 5 mm thick fast plastic scintillators for both Scint1 and Scint2, placing at the sample position with a gap of 20 mm. After passing

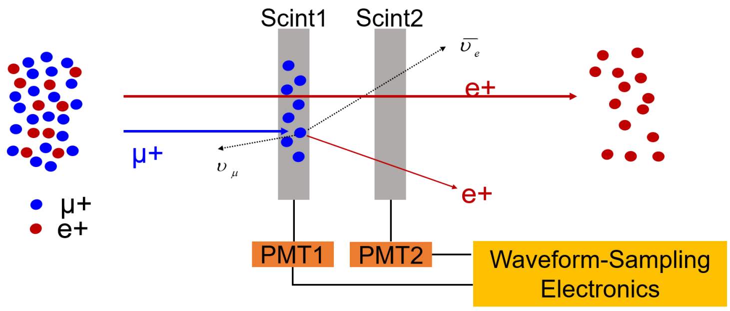

Figure 5. Muon beam intensity measurement and discrimination of positrons.

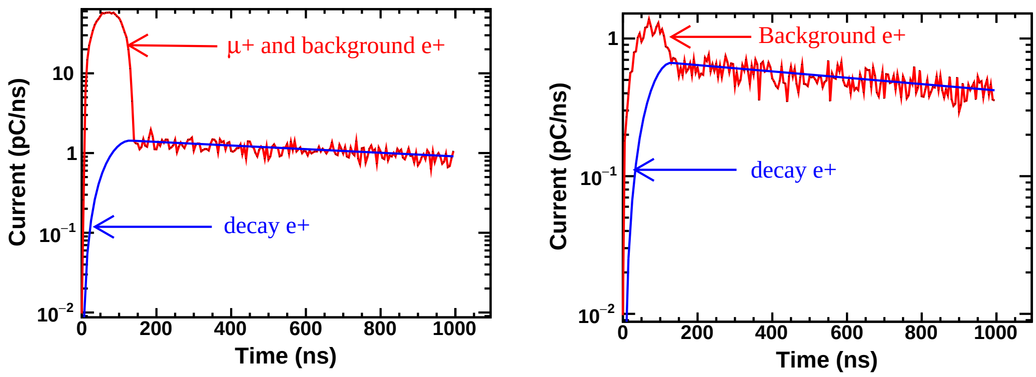

Figure 6. Schematic layout of the μSR spectrometer.

through a thin beam window, muons deposit all 3.27 MeV in Scint1 and the positrons deposit 0.86 MeV in both scintillators. The average energy for emitting a fluorescent photon in the scintillator is about 100 eV. The photon collection efficiency is set to 1% and the quantum efficiency of PMT is 10%. Then we can calculate the number of particles as a function of time from Scint1 and Scint2, as shown in figure. 6. From our simulation the accuracy of the reconstructed number of positrons in the surface muon beam is better than 20% when the fraction of the positrons is lower than 1%.

7. Summary and project schedule

In this report we briefly described the current design status of MELODY. We will use up to 5 Hz proton pulses to hit on a stand-alone carbon target. We designed a surface muon beam and a decay muon beam for various muon applications, and as a start-up we will build the surface muon beam. We reach a high single pulse intensity of 1.6×10^5 μ^+/s within a beam spot of ϕ30 mm. A μSR spectrometer is designed with 2800 detector units to reach a reasonable counting rate. Sample environment is designed to host low temperature experiments with longitudinal and transverse magnetic fields. We also outline a strategy of measuring the high single-pulse intensity and the fraction of the positrons. More tests are needed to

MELODY has been listed in the CSNS II project which will officially start from January 2023. We expect to start the infrastructure construction in the summer of 2023. The whole project will take 6 years including the construction and commissioning of the beamline and spectrometer, and we expect to welcome the first group of users by 2029.

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