Target Design of MELODY

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Abstract. The Muon station for sciEnce, technoLOgy and inDustrY (MELODY) is foreseen to be the first muon source in China and to be located at the China Spallation Neutron Source in Dongguan. The stand-alone target station has been studied for the surface muons and the pions production. In this report, we aim to describe the design of the target station, including the mechanical design, the radiation shielding and optimization of the target in order to provide the highest rates of surface muons and pions to the capture solenoids under certain emittance selections.

1. Introduction

MELODY is intended for muon science and principally for μSR (Muon Spin Rotation Relaxation Resonance) experiments and will be the first muon source in China. It will be located at CSNS, the China Spallation Neutron Source in Dongguan [1]. CSNS is the first spallation neutron source in China that completed the Phase-I construction and entered operation in 2018. Its proton accelerator layout consists of an H^- Linac of 80 MeV, a rapid cycling synchrotron of 1.6 GeV and beam transport lines, working at a repetition rate of 25 Hz. The final proton beam to the spallation target operates currently at a power of 100 kW. In Phase-II (or CSNS-II), the beam power will reach 500 kW.

Table 1. Main parameters of MELODY.

MELODY	Power (MW)	Proton Ek (GeV)	Rep. Rate (Hz)	surface muons μ^+/sec	surface muons Polarization	beam spot (mm)
@CSNS-II	20	1.6	1	10^5	$\geq 90\%$	30
UPGRADE	100	1.6	5	10^4–10^7	50%–90%	30

MELODY will extract one of the 25 pulses from the RCS to produce muons during CSNS-II. Initially, only one μSR beamline and one spectrometer are scheduled. For upgrading MELODY, an extra μSR and new decay muon beamlines are being studied with up to 5 spectrometers.

The main parameters for the principal and the upgrade modes of MELODY are presented in table 1. The project status is presented in these proceedings [2].

In this article, a summary of the target design of MELODY is presented, concerning mainly the production of surface muons and pions and the shielding studies.

2. Target design for MELODY

For the target station of MELODY, a slab of graphite is used as a target for the primary protons to produce the surface muons and the pions, which is placed inside a steel vacuum vessel. Since the spent protons after the target are not utilized by another experiment, the target vessel is integrated with a beam dump of a mild steel with a graphite core as can be seen in figure 1. The surface muons are collected at 123 degrees with respect to the direction of the primary protons by a capture solenoid 50 cm away from the center of the slab.

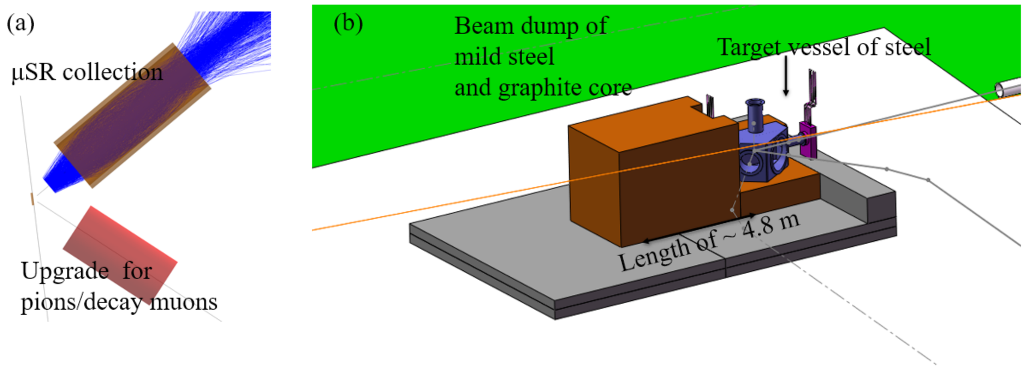

Figure 1. Schematics of (a) the collection and (b) the target vessel integrated with the beam dump.

2.1. The proton target for surface muons and pions

The extracted proton beam from the rapid cycling synchrotron with a kinetic energy and power of 1.6 GeV/c and 20 kW, respectively, will be transported to the target station of MELODY. After investigating many materials, a slab of graphite is chosen for producing surface muons and pions while interacting with the protons. The graphite produces less neutron radiation than higher atomic number materials and adequate rates of surface muons and pions, once the interaction of the proton beam with the target is optimized correctly. It has been also proved a reliable solution for a long-term use with appropriate cooling in the accelerator-driven muon and also neutrino experiments like at SμS at PSI [3], ISIS Muon Facilities at RAL [4], T2K/HK at J-PARC [5] and CNGS at CERN [6].

Figure 2 displays, schematically, the two best proton-target configurations according to our studies and a typical one, using the same length of interaction of the proton beam with each target type: a) The semi-interaction configuration, displacing the slab sideways from the proton beam on the horizontal plane. b) The rotated one, rotating the slab with respect to the proton beam direction and simultaneously increasing its large surfaces. c) The classic one, where the symmetric axis for the protons and the target is the same. Our studies with FLUKA [7] and G4beamline [8] Monte Carlos show that once the slab is displaced on the horizontal plane or the slab is rotated with respect to the proton beam direction, there is an increase at the rates of surface muons because of the optimized ranges of pions in the target or the increase of the dimensions for the large surfaces of the slab, respectively. Both configurations have been studied

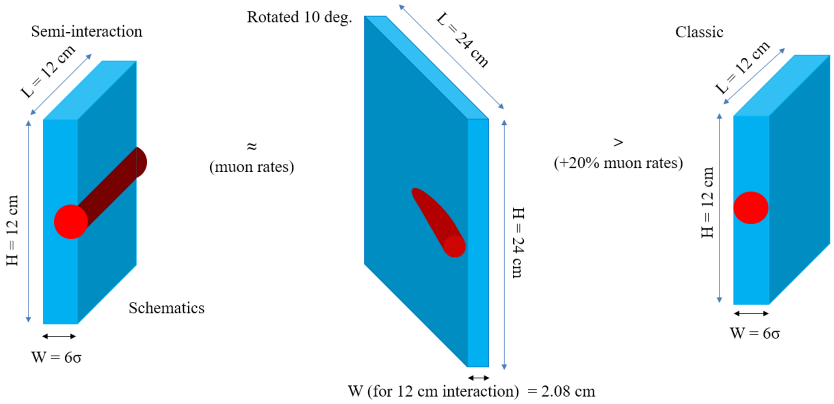

Figure 2. Schematics of the two best proton-target configurations studied: the semi-interaction and the rotated 10 degrees ones with the addition of the classic one.

also before with similar results in [9], [10] and [11]. Furthermore, other configurations have been studied like doublets, triplets with several rotations, and other surface geometries without being better under our selection criteria.

2.2. Surface muon rates

For the optimization of the target and therefore the production of surface muons, we use the following layout and criteria in the simulation: a) A circular virtual detector with a radius of 10 cm located 20 cm away from the center of the target (at the start of the fringe field of the capture solenoid), on the direction of the muon beam at an angle of 123 degrees with respect to the primary protons. b) A transverse emittance selection of 5000 π mm mrad (and secondary of 10000 π mm mrad) representing the acceptance of the beamline downstream from the target. Under these criteria, our studies show that a length of interaction of the protons with the target of 12 cm (also the length of the slab) is sufficient to produce the maximum number of surface muons; any longer target does not improve their rates. For the semi-interaction, we keep using the same size of 12 cm for the height of the slab, although our studies indicate that a reduced size can be used; the width of the slab is parametrized in terms of the size (σ) of the gaussian proton beam and is 6σ. For the rotated target, its length and height are expanded by a factor of 2, while its width is calculated according to the rotation angle to maintain the same length of interaction. Using an interaction length of 12 cm, about 22% or 25% of the protons will be interacting (assuming full interaction of the beam) once the density is 1.8 g/cm^3 or 2 g/cm^3, respectively. Since we are not aware of the final density of graphite now, the simulation shows that the rates would be almost proportional to the density ratio of graphite as expected. We also simulated several parameters for the gaussian proton beam: a) Primarily, $\sigma_x = \sigma_y = 0.33$ cm and no divergences. b) Recently, $\sigma_x = 0.29$ cm and $\sigma_y = 0.66$ cm with or without divergences, without seeing any significant changes for the rates.

Under the above criteria, there is an increase of 20% at the rates of μ^+ with momentum $P_\mu \leq 29.8$ MeV/c for both the semi-interaction and the rotated configurations compared to the classic one. FLUKA predicts that these rates are of the order of O(10^7) or O(10^8) μ^+/sec for the 5000 or 10000 π mm mrad selection, respectively, with an average polarization of muons on their beam axis greater than 90%. For the semi-interaction and the rotated target configurations, the best results are found once the target is displaced sideways by $-1\sigma_x$ to $-2\sigma_x$ on the horizontal plane with respect to the center of the proton beam, and once the rotation angle is small at 5 degrees or 10 degrees, respectively. We choose the semi-interaction because of the smaller

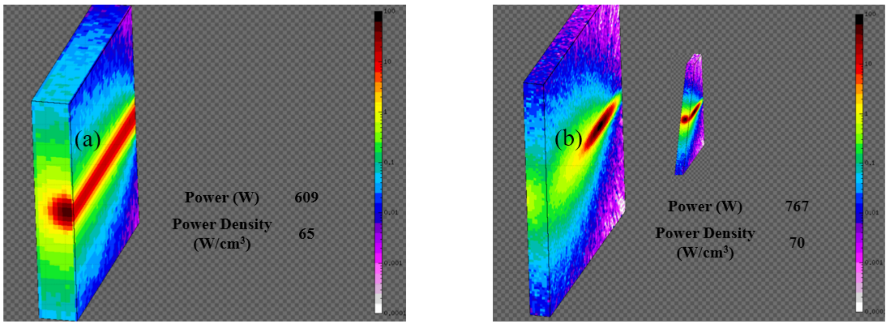

Figure 3. Power densities (in W/cm^3) distribution for (a) the semi-interaction and (b) the rotated 10 degrees configurations as calculated in FLUKA (target sizes not to scale).

dimensions. In addition, the power densities for the semi-interaction are slightly lower as calculated and plotted in FLUKA with a statistical error of 0.7% and FLAIR [12], respectively, as can be seen in figure 3. The total power deposited into both targets cannot be definitive since the dimensions of the slabs are not completely optimized. Lastly, the cooling method for the slab is under study.

Table 2. Muon rates: FLUKA vs. G4beamline with the same virtual detector layout. The statistical errors are less than 1% and 3% for the total and selected muons, respectively.

MELODY	μ^+/sec (10^8)			μ^-/sec (10^8)	$\mu^+ + \mu^-$	μ^+/μ^-
		$P_\mu \leq 29.8$ MeV/c				
	total	total	5000 π mm mrad	total	total	total
FLUKA	44	6	0.47	20	64	2.2
G4bl/Bertini	58	3	1.3	16	74	3.6

2.3. FLUKA versus G4beamline for μ^+ and μ^-

For an assessment of the muon production by simulation at MELODY, we compare the results of FLUKA and G4beamline using the same parameters. Figure 4 and table 2 show the muon rates as function of the momentum and their absolute values, respectively, as predicted by both Monte Carlos. G4beamline with the appropriate Bertini model for lower energies predicts a factor of 2.2 or 2.7 more μ^+ with momentum $P_\mu \leq 29.8$ MeV/c with or without emittance selection, respectively. FLUKA predicts more μ^- rates and a lower ratio μ^+/μ^- of 2.2. The polarizations are similar. For the beam divergence, we checked the angular distribution of μ^+ with $P_\mu \leq 29.8$ MeV/c with respect to the beamline direction by plotting (not shown) the average transverse momentum of the muons as function of momentum and found that is similar. Furthermore, G4Beamline with the INCL model predicts even more μ^+ with $P_\mu \leq 29.8$ MeV/c by a factor of 3 than FLUKA.

2.4. Angle of collection for surface muons and pions

At MELODY, the collection of surface muons and pions is made only on one side with respect to the proton beam, sideways backward and forward, respectively, as schematically presented in figure 5(a), due to the civil engineering. For the surface muons, our studies have shown that

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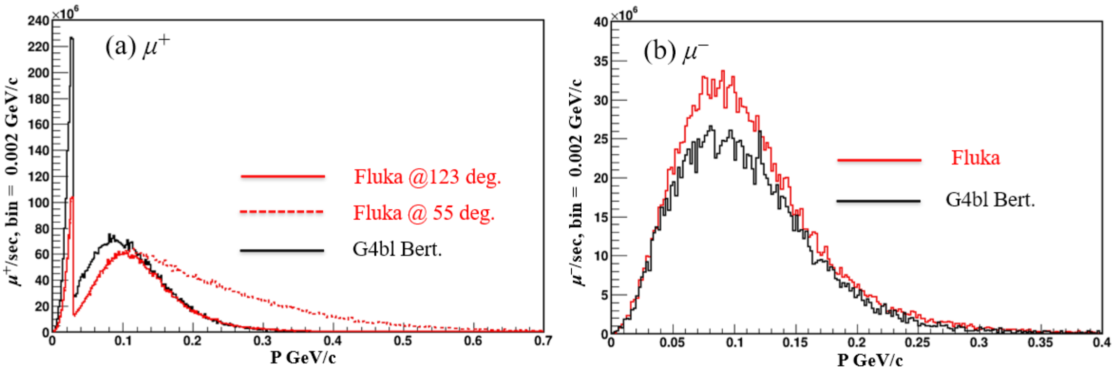

Figure 4. Muon rates as function of momentum for μ^+ and (b) μ^-. FLUKA and G4beamline in red and black, respectively. The density of 2 g/cm^3 is used in both MCs.

their rates are similar for a wide range of collection angles between 35 degrees and 135 degrees under our selection criteria, and thus we choose the 123 degrees for their collection in order to fit better the muon beamline downstream from the target. For upgrading MELODY with decay muons, the lower the angle of collection of pions the higher is their momentum due to the direction of the protons, and as a result, we choose the 50 degrees in order to have sufficient pions with momentum $P_\pi \leq 0.6$ GeV/c, as can be seen in figure 5(b), and therefore sufficient decay muons for the future muon experiments. Our studies have shown that the total π^+ rates are of the order of O(10^{11}) π^+/sec at the virtual detector.

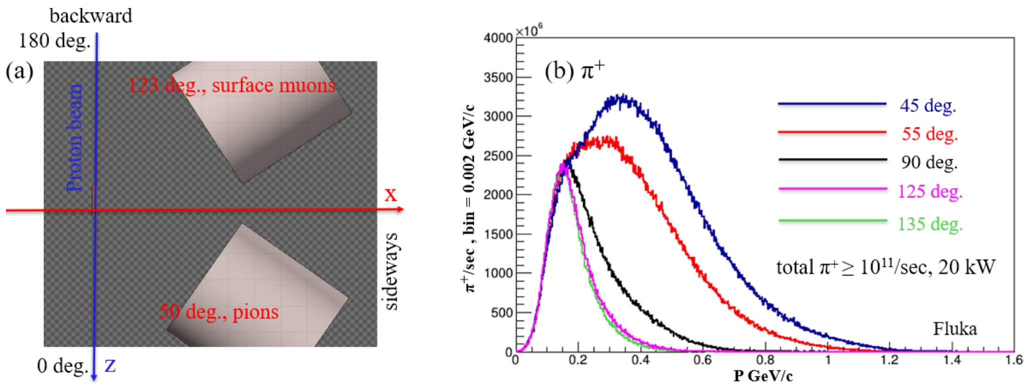

Figure 5. (a) Schematics for the collection and (b) π^+ rates as function of momentum for different angles of collection.

2.5. Shielding and radiation

The shielding of the target station must comply to the radiation rules of CSNS and protect MELODY and the nearby experimental areas. With a proton beam power of 20 kW and a target of graphite, materials like mild steel and concrete with several meters of depth are being studied for shielding. The beam dump consists of a mild steel shielding and a graphite core to stop the spent protons, so that less neutrons will be produced. In the case of the maintenance of the target, the roof shielding blocks are foreseen to be removed by a crane to have access to the target vessel. Our preliminary studies show that: a) The prompt radiation at the target station drops to a few μSv/h after several meters of mild steel and concrete as can be seen in figure 6(a), complying with the CSNS rules. b) The dose residual radiation is at the order of Sv/h and mSv/h at an accelerator shutdown after 100 days of operation and two months later, respectively, as can be seen in figure 6(b), indicating the necessity of a remote handling for the target maintenance.

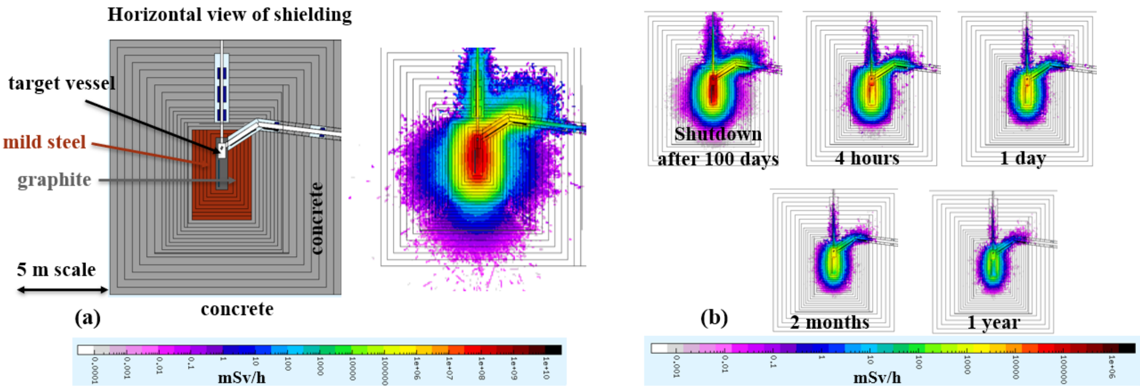

Figure 6. (a) Schematics of the shielding layout with the prompt doses and (b) the related residual doses.

3. Summary
The design of the target station of MELODY is presented under a primary proton power of 20 kW. We select a small rectangular slab of graphite to collect surface muons rates of the order of O(10^7) μ^+/sec near the target, with a collection angle of 123 degrees with respect to the protons and under a transverse emittance of 5000 π mm mrad. For a future upgrade, a decay muon beamline is foreseen from pions collected at a lower collection angle of 50 degrees with total rates of the order of O(10^{11}) π^+/sec. The shielding of the target station will be based on layers of mild steel and concrete to comply with CSNS radiation rules.

Acknowledgments
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