Simulation Study of surface muon transmission at S-line for the Mu 1S-2S ionization experiment at J-PARC

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This note describes the simulation study for the surface muon transport at S-line for Mu 1S-2S spectroscopy experiment[1], including surface muon intensity and the tuning of S-line (S2). The entire simulation package from surface muon to the slow muon beam line has already been desribed in the reference note[2], which consist of similar studies for D-line. This note will mainly focus on the characteristics of the simulation on S-line.

1 S-line Overview

Now the S2 area at J-PARC MLF is still under construction. The muon beam in the MLF is double pulsed now and the current proton power is 500 kW, which may upgraded to about 1 MW in the future[3]. The layout of the S-line in the experimental hall No. 1 of the MLF building is shown in Fig. 1. The S-line consist of three bending magnets and several quadruples to provide beam bending and focusing.

The S1 and S2 area shares the common part of S-line before the third bending magnet (SB3). The slits (SSL1) was put between the second magnet (SB2) and the triplets (SQ10-12), as shown in the Fig. 1. The slit helps to reduce the beam size but makes the beam intensity lower as well. The usual condition for SSL1 is to square the beam by 100 mm * 40 mm (horzontally * vertically). Both S1 and S2 will be affected by SSL1.

For the S1 area, there is another separated slit (SSL2-1, 40 mm * 40 mm) after SB3 and before SQ16-18. While for S2, another slit after SB3 (SSL2-2) is not necessary (especially for Mu 1S-2S) to use. Higher intensity of surface muon would be appreciated if the second slit (SSL2-2) is not used, or open to more space (for example 240 mm * 240 mm).

An automatic beam tuning program, named "ForTune" developed specifically at MUSE[4], was used to obtain a well-focused muon beam (about 20 mm) at the sample position the end of S-line (S1). The tuning of the beamline slits led also to the suppression of positron contamination in the muon beam and a narrower beam spot size at the target position. A beam collimator with a diameter of 40 mm was placed at the end of the beamline just in front of the sample position to reduce the beamline related background.

Currently, the surface muon intensity at S1 was measured with SSL1, SSL2-1 and the collimator on. The surface muon intensity at S1 was meaured to be about $1.9 \times 10^5/s$ for 500 kW proton power and for the single pulse[4].

In order to estimate the surface muon intensity at S2, the measurement at S1 area and the Geant4 simulation at S2 area (G4Beamline) shoulde be combined. The strategy is to start from the

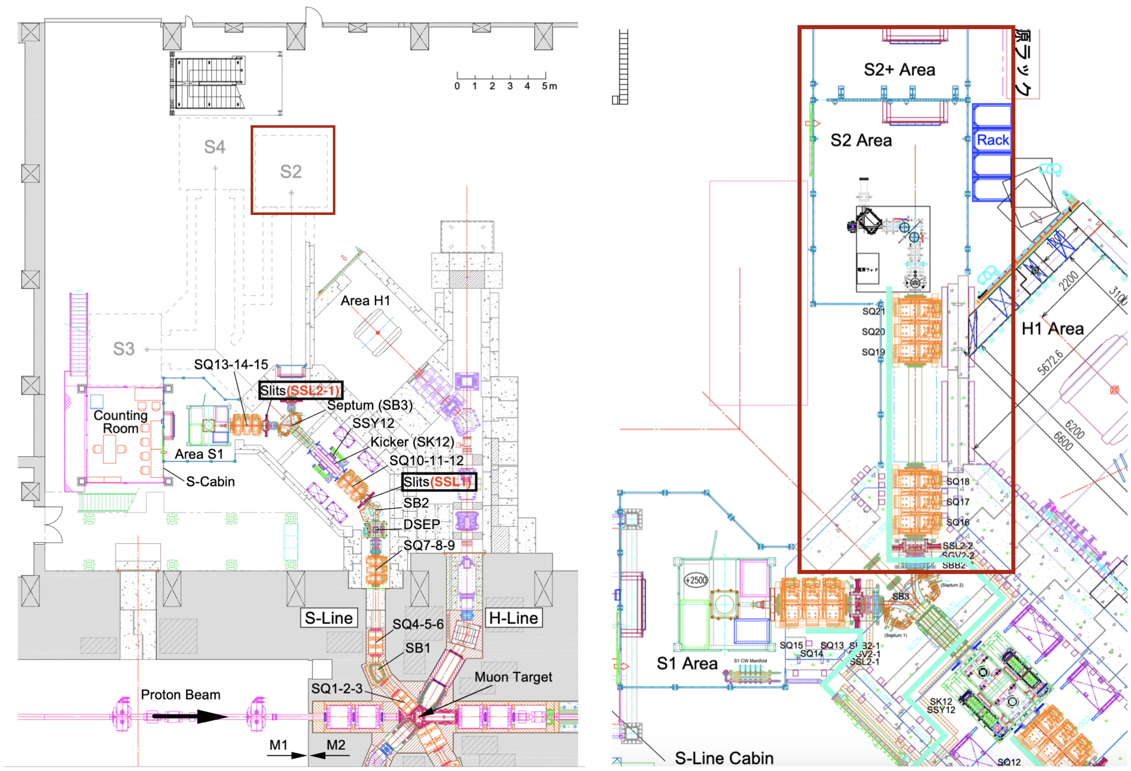

Figure 1: S-line overview. Left one is the overview of S1 and S2. Right one is the S2 scheme in the future plan. From [3]. The SSL1 and SSL2-1 are in the black boxes.

surface muon intensity at S1 area, then using the simulation at S1 to simulate the similar conditions at S2 area in the future (such as to remove the SSL2-1, the collimator). Then the efficiency from simulation result is used to estimate how the transmission efficiency and the surface muon rate would be on S2 area, as shown in Fig.2.

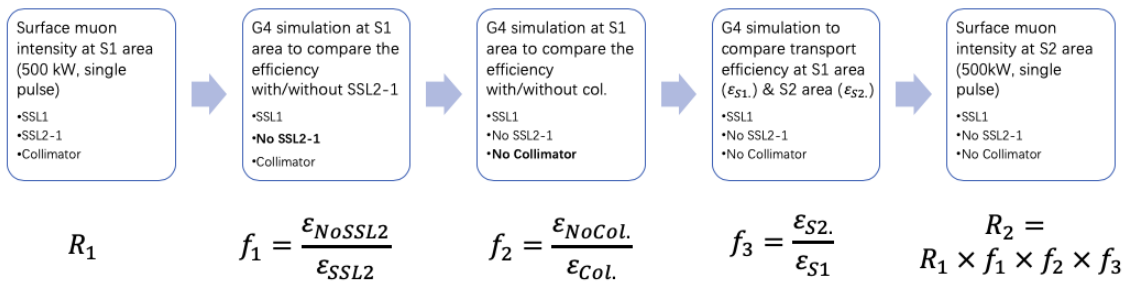

Figure 2: Strategy to estimate the surface muon intensity R_2 at S2. Since the SSL2-2 and the collimator are not necessary for Mu 1S-2S experiment at S2, SSL2-1 and the collimator was remvoed at S1 simulation step by step to check the change of the efficiency

2 Surface muon simulation by G4beamline

2.1 Simulation for S1 area

The G4Beamline [5] simulation package was used to do the simulation for the S1 area for different conditions and then applied to S2 simulation. This simulation package is based on Geant4.

The parameters used in the S1 simulation comes from the real specifications. The initial beam profile before the s-line transmission was assumed to be gaussian distribution for the input of Geant 4 simulation. The initial beam was shot in the z direction. Details are in the Table 1.

Table 1: Initial surface muon distributions

Mean momentum P	28.5 MeV/c
σ_P	0.5 MeV/c
σ_x	17 mm
σ_y	24 mm
$\sigma_{X'}$	0.208 mm
$\sigma_{Y'}$	0.208 mm

Starting from the surface muon intensity of 1.9×10^5 at S1 at 500 kW proton power and single pulse with SSL1 and SSL2-1 ON, several conditions was changed step by step to see how the efficiency and the intensity would change accordingly, as in the Table 2.

Table 2: Summary of the S-line (S1) simulation

SSL1 [mm × mm]	SSL2-1 [mm × mm]	Collimator	$N_{initial}$	N_{final}	Efficiency	Scaled intensity (500 kW, single pulse) [/s]
100*40	40*40	ON	1E+06	574	0.00057	1.9×10^5
100*40	40*40	OFF	1E+06	586	0.00059	1.9×10^6
100*40	240*240	OFF	1E+06	7236	0.0072	2.4×10^6
240*240	240*240	OFF	1E+06	10646	0.011	3.5×10^6
100*40	240*240	ON	1E+06	4948	0.0050	1.6×10^6
240*240	240*240	ON	1E+06	6931	0.0069	2.3×10^6

On the Table 2, the initial surface muon intensity 1.9×10^5 is the measured one. From Table 2, The effect of the change of the conditions in S1 can be summarized:

- The effect of removing SSL2-1:

$$f_1 = \frac{\epsilon_{NoSSL2-1}}{\epsilon_{SSL2-1}} = 4948/575 = 9.1$$

- he effect of removing collimator:

$$f_2 = \frac{\epsilon_{NoCol.}}{\epsilon_{Col.}} = 7236/4948 = 1.5$$

From the S1 measurement[4], the factor $f_1 = \frac{\epsilon_{NoSSL2-1}}{\epsilon_{SSL2-1}}$ was measured to be 4.4 when the SSL2-1 was removed and the collimator ON. It is lower than the simulation result 9.1. Therefore note that there might be a uncertainty in the estimation by the factor of about 2.

2.2 Simulation for S2 area

In the S2 simulation, the last three triplets was tuned to have optimized beam size and the profile for the target at S2. The strategy of Geant-4 simulation is to tune the last triplet (SQ19-21). SQ19 and SQ21 are for the Y-focus while SQ20 for the X-focus. The focusing position of the beam will be changed when the values of either triplet current is changed. The size of the beam is supposed to be shifted by scaling all the three current values on the BMs.

Considering laser shoting condition, the profile at the end of the beam line was tuned specifically to be shrinked vertically and slighted extended in horizotally so that more events would be able to get into the laser ionization area after surface muon stopped inside the aerogel.

While the final position of the lst triplet (SQ19-21) is not decided, the position of the target at the end of the S2 still has some uncertainty. But the tentative position of the last triplet is 355 mm away from the surface muon target (aerogel) at S2 area. Although the position in the future may be shifted slightly, but the rough simulation reveals that the small shift will not strongly affect the focusing condition and the size & intensity of the surface muon.

Therefore, with the SSL1 shared by S1 and S2, the last triplet (SQ19-21) of S2 was tuned by the scale factor (the detailed tuning process are in the appendix). The scale factor represent the

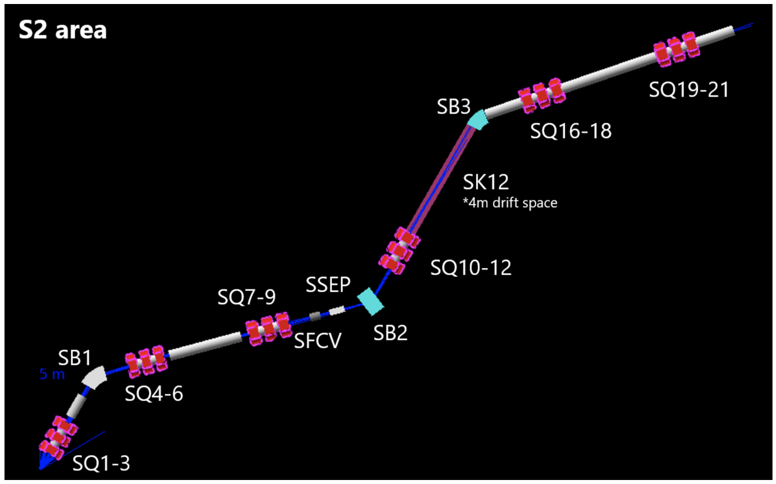

Figure 3: S-line (S2) simulation overview

magnitude of the current value applied on each magnet (Maximum 1.675 T/m, 375 A). The best results are in the Table 3.

Table 3: Summary of the S2 SQB19-21

SQB	scale factor
19	0.29
20	-0.43
21	0.19

Based on the specifications of SQ19-21 from Table 3, the simulation result on S2 are shown in the Table 4.

As S1 and S2 shares the same SSL1, the most realistic setup for Mu 1S-2S experiment at S2 in the future is that SSL1 set to be 100*40 mm^2 while SSL2-2 240*240 mm^2, without the collimator.

From Table 2 (S1) and Table 4 (S2), under the same specifications (SSL1 100*40 mm^2, SSL2 240*240 mm^2, collimator OFF), the efficiency of beam line transport for S2 and S1 was compared. The transport efficiency for S-line to S1 area is 0.00724 while S2 is 0.00717, thus:

$$f_3 = \frac{\epsilon_{S2}}{\epsilon_{S1}} = 0.00717/0.00724 = 0.99$$

The transport efficiency for S1 and S2 are almost the same. Therefore, the intensity of surface muon beam at S2 area is estimated to be

$$R1 \times f_1 \times f_2 \times f_3 = 1.9e5/s \times 9.1 \times 1.5 \times 0.99 = 2.4 \times 10^6/s$$

under 500 kW proton power and single pulse.

Table 4: Summary of the S-line (S2) simulation

SSL1 [mm × mm]	SSL2-2 [mm × mm]	Collimator	$N_{initial}$	N_{final}	Efficiency
100*40	240*240	OFF	1E+08	717135	0.00717
240*240	240*240	OFF	1E+08	1085249	0.0109

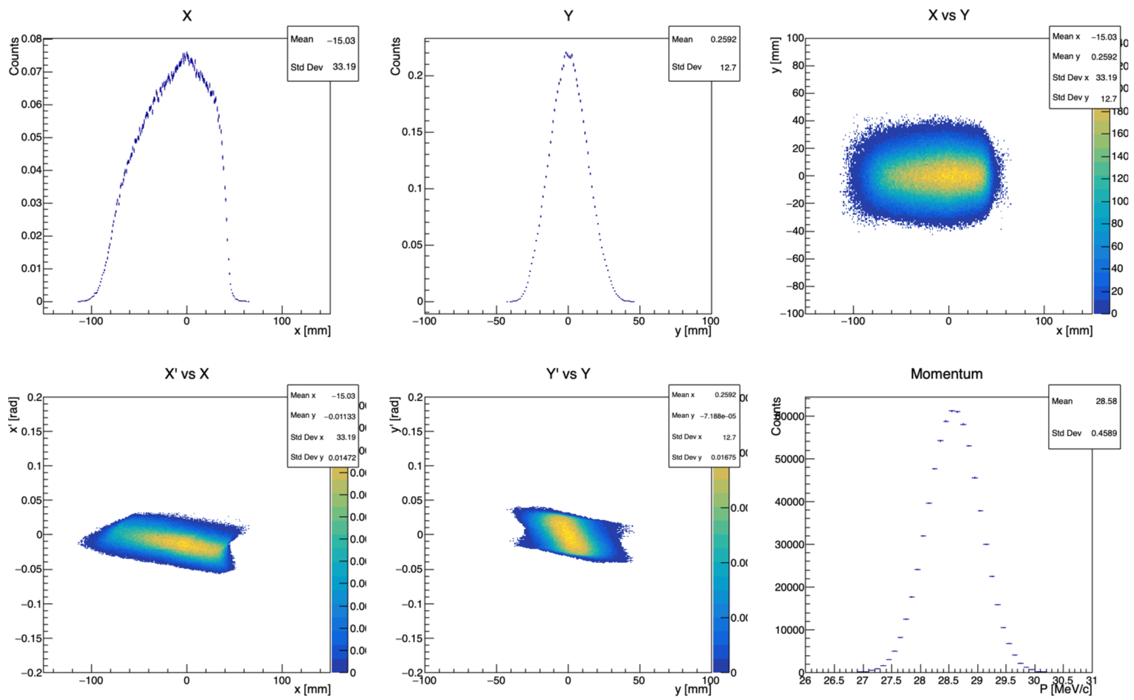

Figure 4: Final surface muon distributions after transmission at S2 area, including X,Y,X',Y' and momentum distribution. The virtual detector is 163 mm upstream from the aerogel target position.

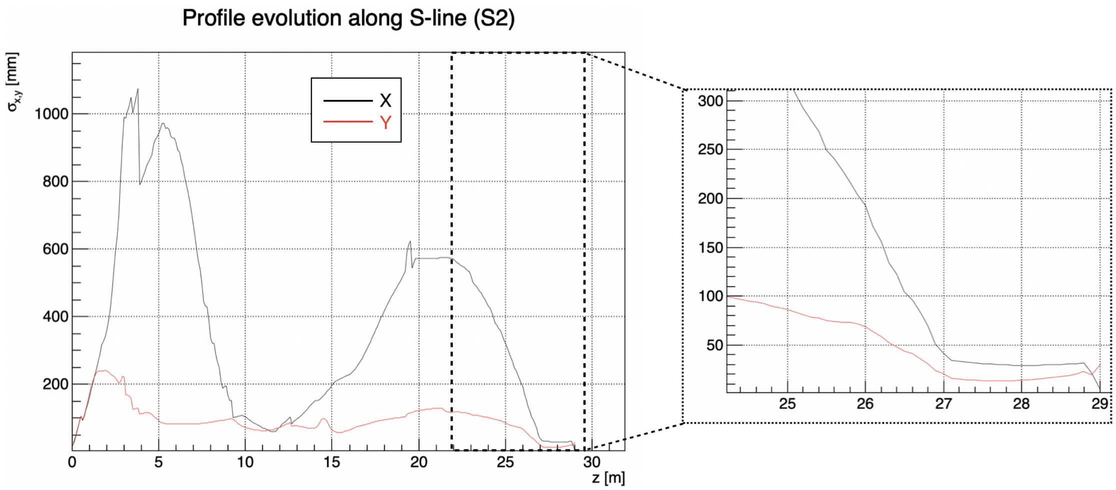

Figure 5: Beam envelope along the S-line. The proton target is at 0 m, while the aerogel target at S2 area is at 27.34 m.

The profile at the end of S2 were produced (the detector is 163 mm away from the aerogel target position), as shown in the Fig. 4. The beam envelope along the S-line to S2 is shown in the Fig. 5.

3 Summary

Finally, all the important simulation results are summarized in the table 5. The profiles will be very useful for the further simulation of surface muon stopping inside the aerogel target and the muonium yield for the laser ionization.

Table 5: Summary of the S-line (S2) simulation at the S2 target position

transport efficiency along S-line to S2	0.00717
Surface muon intensity at S2 (500 kW, single pulse)	2.4×10^{6}/s
σ_x	33.19 mm
σ_y	12.7 mm
Mean Momentum P	28.58 MeV/c
σ_P	0.46 MeV/c

Reference

[1] Uetake-san's slide from KEK workshop,

https://kds.kek.jp/indico/event/32734/contributions/160173/attachments/127747/152036/191127-Uetake-s.pdf
[2]Ce Zhang, Simulation Study of Surface muon beamline, thermal muon production and extraction for the Mu 1S-2S spectroscopy experiment at D-line
[3] JPS Conf. Proc. 21, 011061 (2018)
[4] private talk from A.Koda-san.
[5] http://public.muonsinc.com/Projects/G4beamline.aspx

Appendix

Table 6: Simulation tuning of SQ19-21 on S2

SQ19 (Y-focus)	SQ20(X)	SQ21(Y)	N_initial	N_final	X' [rad]	σ_x[mm]	σ_y [mm]	Note
				SQ19 tuning				
0.30	-0.67	0.22	1E+05	986				
0.40	-0.67	0.22	1E+05	1064				Best
0.44	-0.67	0.22	1E+05	1063				
0.45	-0.67	0.22	1E+05	1062				
0.50	-0.67	0.22	1E+05	980				
0.60	-0.67	0.22	1E+05	747				
				SQ20 tuning				
0.40	-0.40	0.22	1E+05	1059				
0.40	-0.50	0.22	1E+05	1063				
0.40	-0.60	0.22	1E+05	1064				Best
0.40	-0.70	0.22	1E+05	1056				
0.40	-0.80	0.22	1E+05	934				
				SQ21 tuning				
0.40	-0.60	0.10	1E+05	1064		36.50	43.70	
0.40	-0.60	0.15	1E+05	1064		33.40	38.70	
0.40	-0.60	0.22	1E+05	1064		30.90	31.60	
0.40	-0.60	0.30	1E+05	1064		30.90	23.80	Best
0.40	-0.60	0.40	1E+05	1064		34.50	17.00	
0.40	-0.60	0.50	1E+05	1064		40.70	18.30	
Further tuning for reducing X' and shrinking in the Y-direction according to laser region setup								
0.36	-0.54	0.27	1E+05	1064	0.025	23.20	16.70	
0.32	-0.48	0.24	1E+05	1064	0.022	21.80	13.70	
0.28	-0.42	0.21	1E+05	1064	0.018	16.9	14.3	
0.24	-0.36	0.18	1E+05	1064	0.014	40.0	16.87	
0.24	-0.36	0.22	1E+05	1064	0.018	35.7	19.5	
0.29	-0.43	0.19	1E+05	1064	0.014	32.2	11.6	Best