Simulation Study of slow beam line for the Mu 1S-2S experiment at J-PARC

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This note describes the simulations for the extraction and the transport of the thermal muons after laser ionization. This study is for the Mu 1S-2S experiment proposed at J-PARC S-line (S2 area). Independent notes[1, 2] describes the previous steps, including S-line simulation, surface muon stopping, the muonium(Mu, μ^+e^-) formation processes.

Note here, the thermal muon events generated in the MLF D-line conditions are used in this simulation notes. In the future, Mu 1S-2S experiment is proposed to use S-line (S2 area). Although the conditions are not exactly the same, the slow muon beam line transport efficiency would not be expected to change a lot. The efficiency result for the slow muon beam line in this study should still be a good estimation.

1 The slow muon beam-line

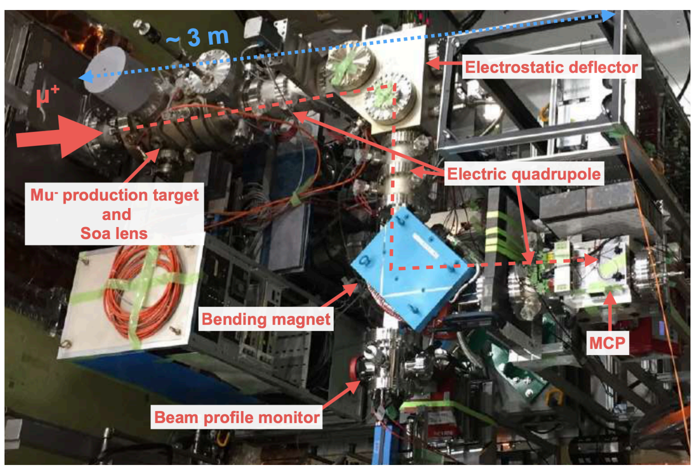

Figure 1: The picture of the slow beam line

After thermal muons are generated by laser ionization from muonium, The generated thermal muons will be extracted by electro-static lens (SOA) and be transported to the MCP detector through the slow beamline, which consist of the electrostatic deflector (ED), electric quadrupoles (EQs) and the Bending magnet (BM)[3]. The beamline specifications are taken from the reference of the previous Mu^- production experiment[3] and the anti-Mu^- experiment beam test on Feb. 2019.

The entire beamline setup is shown in Fig.1. Firstly, the SOA lens are employed to initially extract the thermal muons. The SOA lens consists of two mesh electrodes and three cylindrical electrodes. The first mesh electrode covers the downstream surface of the silica aerogel target. The specifications of the SOA are in the Table 1.

Table 1: Specifications of SOA

Electrode	Applied Vol. [kV]
SOA-target	20.00
SOA-S1	18.94
SOA-S2	18.04
SOA-S3	16.00

Table 2: Specifications of ED

ED	
Curvature radius [mm]	400
Maximum withstand Voltage [kV]	2.5
Electrode aperture [mm]	100

Table 3: Specifications of BM

BM	
Current [A]	20
Voltage [V]	6
Magnetic field [Gauss]	300

The decay positron from the incident muon or the electron produced by the field emission at the SOA lens are eliminated by using the ED and the BM. The applied voltage for ED is 5 kV to bend the charged particle with 20 keV, as shown in the Table 2. The specifications of BM are in the Table 3. Only the thermal muon can be transported to the MCP using the ED and the BM. The voltage settings and the power supplies of the EQ's are shown in the Table 4.

Table 4: Specifications of EQ

Electrode	Applied Vol. [kV]
SOA-target	20.00
SOA-S1	18.94
SOA-S2	18.04
SOA-S3	16.00

2 Simulation study

In the simulation, extraction and transmission of thermal muon is simulated by the muSRsim package (based on GEANT-4)[4, 5]. Fig. 2 shows the schematic view of the beam transport simulation, which consists of ED, EQ's and the BM, the same as the real beam line.

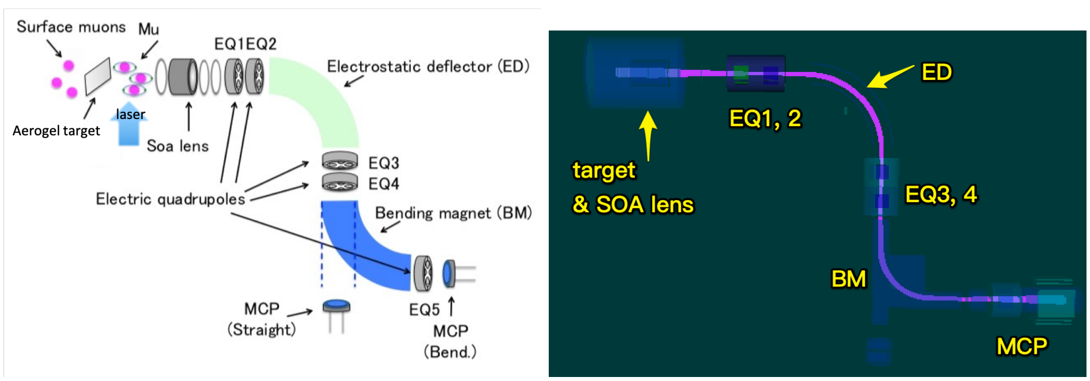

Figure 2: The schematic view of the beam transport (left) and its realization in the muSRsim package simulation (right).

The electric fields of the SOA lens, the ED, and the EQ's, and the magnetic field of the BM are generated with OPERA and implemented in musrSim[6]. Fig. 3 shows the example of SOA and ED field distribution inside OPERA[7].

In total 1.1×10^8 events was generated in the simulation at the surface muon production target and 7 063 080 surface muons at the entrance of D2 area. Fig. 4 shows the initial space distribution at the laser ionization area. Fig. 5 shows simulated phase-space distributions of the transported muon at the MCP. The number of the detected events is defined as the events within the effective area of the MCP (ϕ42 mm). Further tuning to focus the beam on the MCP is in progress.

The number of the initial events and the detected events in the final MCP in the simulation are 1983 and 1521 respectively. The number of muon in the decay loss is 251 out of 1983. Therefore the efficiency due to the decay loss is

$$\frac{(N(total) - N(decay))}{N(total)} = (1983 - 251)/1983 = 0.87.$$

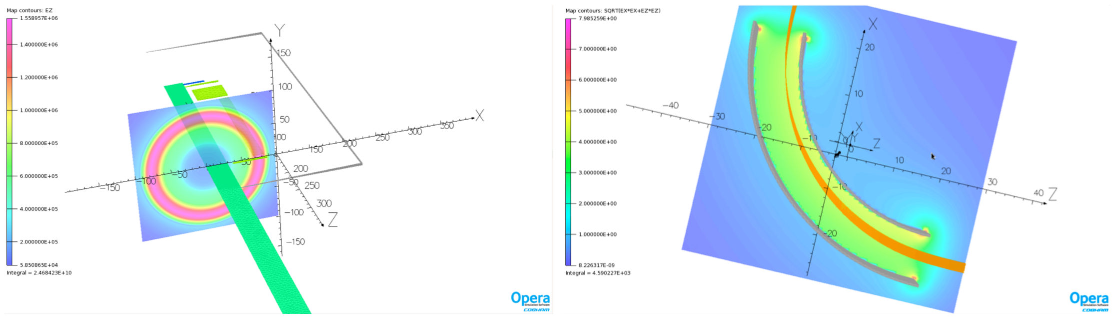

Figure 3: Field map in the OPERA. left is the SOA field in the beam direction (z-axis) on the Transverse plane. Right one is the ED field, the E-field in the r-direction on the horizontal plane.

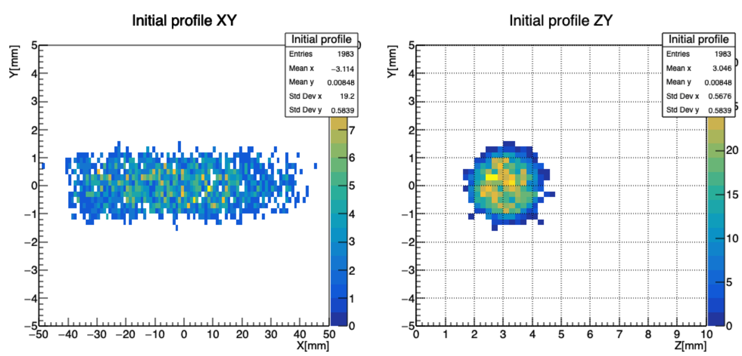

Figure 4: The initial thermal muon source profile for the slow beam-line simulation. Left one is the XY plane, right one is in the ZY plan. The beam is shot on the Z-direction. The laser was assumed to be shot in the X-direction, centered at Z=3, Y=0, with the radius of about 1 mm.

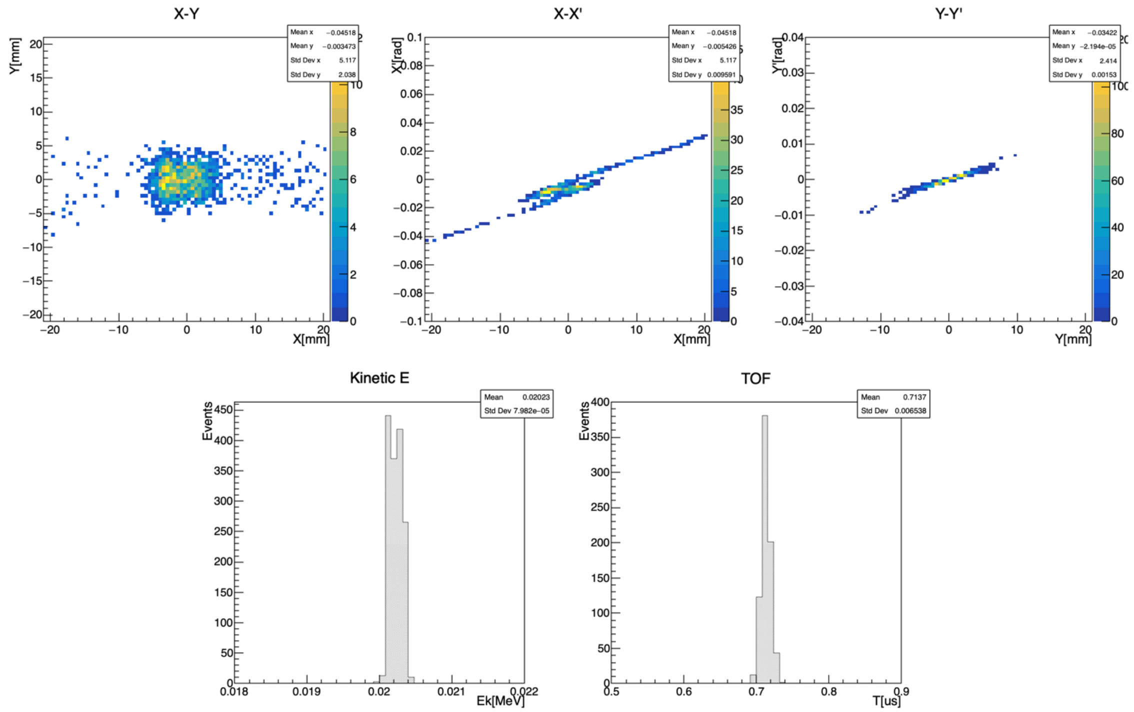

Figure 5: Simulated phase-space distributions, kinetic energy and time distribution for the thermal muon at the MCP detector. The thermal muon beam was roughly tuned to be within the MCP detective area (ϕ42 mm). The mean value of TOF is about 0.71 μs, which include the SOA acceleration process from about 0.2 keV to 20 keV.

The transmission efficiency excluding decay loss is

$$\frac{N(MCP)}{(N(total) - N(decay))} = 1521/(1983 - 251) = 0.88.$$

In short, the total transmission efficiency (including the decay loss) is

$$\frac{N(MCP)}{(N(total) - N(decay))} = 1521/1983 = 0.77.$$

3 Summary

The simulation of surface muon beamline, thermal muon production and extraction for the Mu 1S-2S experiment was developed. Table 4 summarizes the efficiency. In the Table 4, the efficiency of mesh is 0.85 and the detection efficiency of the MCP is 0.90, which comes from the open aperture ratio from Ref. [3].

Table 5: Summary of the slow beam line simulation

	N(initial)	N(left)	efficiency
Decay loss	1983	1732	0.87
Transmission efficiency (Decay loss excluded)	1732	1521	0.88
MCP detection efficiency			0.90
Mesh efficiency			0.85

References

[1] Ce Zhang. *Simulation Study of thermal muon formation at S-line for the Mu 1S-2S experiment at J-PARC*. Tech. rep. Dec. 2019.

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[3] Ryo Kitamura. "Demonstration of the muon acceleration with Radio-Frequency Quadrupole linac". PhD thesis. University of Tokyo, July 2018.

[4] M. Otani et al. "Simulation of Surface Muon Beamline, UltraSlow Muon Production and Extraction for the J-PARC g-2/EDM Experiment". In: *Journal of Physics: Conference Series* 1067 (Sept. 2018), p. 052018. DOI: `10.1088/1742-6596/1067/5/052018`. URL: `https://doi.org/10.1088%2F1742-6596%2F1067%2F5%2F052018`.

[5] "Technical Design Report for the Measurement of the Muon Anomalous Magnetic Moment g − 2 and Electric Dipole Moment at J-PARC". Dec. 2017.

[6] Kamil Sedlák et al. *Manual of musrSim*.

[7] https://operafea.com/. *Opera*.