Simulation of Surface Muon Beamline, UltraSlow Muon Production and Extraction for the J-PARC g-2/EDM Experiment

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Abstract. We have developed a ultraslow muon simulation for measurement of the muon anomalous magnetic moment at the Japan Proton Accelerator Research Complex (J-PARC). The experiment will be conducted at new muon beamline (H-line) at Materials and Life Science facility (MLF) in J-PARC. H-line provides surface muons that thermalizes in a silica aerogel target to form muonium. The generated muoniums are ionized by laser and ultraslow muons are generated. The ultraslow muons are extracted by an electrostatic accelerator and injected to a muon linac. This paper describes the simulation for the surface muons, muonium production, and electrostatic acceleration.

1. Introduction

Though discovery of Higgs at LHC completed the particles predicted in Standard Model (SM) of elementary particle physics, some observations such as dark matter existence indicate new physics beyond SM at some energy scale or interaction scale. One of the clues for new physics is anomaly of the muon anomalous magnetic moment \((g-2)\mu\): A difference of approximately three standard deviations exists between the SM prediction and the measured value (with a precision of 0.54 ppm) of \((g-2)\mu\) [1]. Measurement with higher precision is necessary to confirm this anomaly. Low-emittance muon beams will facilitate more precise measurements, as the dominant systematic uncertainties in the previous experimental results are due to the muon beam dynamics in the muon storage ring.

The E34 experiment at the Japan Proton Accelerator Research Complex (J-PARC) [2] aims to measure \((g-2)\mu\) with a precision of 0.1 ppm. The experiment uses the proton beam from the 3 GeV Synchrotron ring to Materials and Life Science facility (MLF). The proton beam is injected to the graphite target [3] to produce surface muons. The generated surface muons are extracted to one of a muon beamline, H-line [4]. The surface muons stop in a silica aerogel target and some portion forms thermal muoniums \((\text{Mu}, \mu^+e^-)\) [5]. The paired electron in the Mu’s is knocked out by laser and ultraslow muons (25 meV) are generated. The generated ultraslow muons are electro-statically accelerated to 5.6 keV and injected to a muon linac. The accelerated muons
are stored in a high precision muon storage magnet [6], where the time dependence of decay positrons is measured to reveal a muon spin precession. Because the intensity of the ultraslow muons determines the statistical reach of the experiment, the intensity should be evaluated by dedicated simulations.

This paper describes simulations for H-line, Mu production, and electrostatic acceleration of the ultraslow muons.

2. Surface muon beamline

Figure 1 shows the optics design of H-line. H-line is extracted at the angle of 60 degrees forward direction. There is other muon beamline (D-line) in the opposite side of the proton beam. The front-end solenoid magnet (HS1) consisting of eight coils provides capture field and transports the muons to the first bending magnet (HB1). The second and third solenoid magnet (HS2 and HS3) provide a weak focusing field in a opposite direction each other. There is a Wien filter between HS2 and HS3 to eliminate positrons with same momentum to the muons. The second bending magnet (HB2) extracts the beam to an experimental area where some experimental programs [7, 8] are scheduled. Finally the surface muons are focused to the muonium production target by the quadrupole triplet after the fourth solenoid magnet (HS4).

![Figure 1. Optics design of H-line. Blue lines show a typical result for transport of the surface muons.](image)

The surface muon properties on the proton target was estimated using measurements at D-line to avoid discrepancy among the hadron production models. The D-line simulation was developed using g4beamline [9]. The spatial distributions ($\sigma_x = 2$ mm and $\sigma_y = 4$ mm) are determined based on the proton beam profiles. The momentum distributions are implemented with the range of muons in the target material of graphite. Figure 2 shows momentum dependence of the muon intensity at D-line. There is a good agreement between measurement and the simulation result. The surface muon intensity on the proton target was determined based on this result for the H-line simulation. The estimated muon intensity at the proton target is $2 \times 10^9$/s.

The g4beamline simulation for H-line was developed to estimate the surface muon intensity and profiles at the muonium production target. In the simulation, the magnetic fields calculated by OPERA [10] were implemented. The current of each magnet is first tuned based on experience of operating muon beamline such as D-line, and then the optimization algorithm of SIMPLEX is applied so that the intensity at the muonium production target is maximized. Figure 3 shows the estimated profiles at the muonium production target. The profile width in the horizontal and vertical direction differ from each other because the beamline is not free from the momentum dispersion. Ratio of the transportation efficiency between H-line and D-line is estimated to be eleven. The muon intensity is estimated to be $3.2 \times 10^8$/s at the muonium production target.

3. Muonium production

A Mu production simulation is developed to estimate the Mu amount in the laser ionization region. The surface muon beam distributions described in previous section were used as input.
Figure 2. Momentum dependence of the surface muon intensity. Black circle and red circle show simulation and measurement, respectively. Vertical scale of the simulation is normalized by the measured value around 25 MeV/c.

Figure 3. Estimated profiles at the muonium production target. (A) profile in the horizontal direction, (B) profile in the vertical direction.
The muon stopping distributions in the silica aerogel target were estimated using GEANT4 [11]. The 52% of the stopped muon form Mu’s [12]. The simulation for muonium diffusion in the target is based on a three-dimensional random walk in which each step is taken with a speed drawn from a Maxwell thermal distribution and a mean free path. The simulation parameters of the thermal temperature and the diffusion constant were determined from our measurement at TRIUMF [5]. Figure 4 shows comparison between the measurement and the simulation after fitting the simulation parameters. There is a good agreement between the measurement and the simulation.

![Figure 4. Fit of the diffusion simulation to emission data. (A) decay time distribution in a region from 10 mm to 20 mm from the Mu production target, (B) 20 mm to 30 mm, (C) 30 mm to 40 mm. The black histogram is the data and the fit is shown by blue squares. The fit is the sum of the scaled simulation (red histogram) plus an exponential background (blue histogram).](image)

Figure 5 shows the number of ultraslow muons in the laser region as a function of time from average time of the surface muon beam arrival. The laser pulse timing is determined to be 1 μsec so that the number of the ultraslow muons is maximized.

In summary, we calculated the efficiency to produce muonium atoms in laser ionizing region at the time of the laser pulse. The fraction in the ionizing region is $3.8 \times 10^{-3}$. The laser ionization efficiency is based on a calculation assuming individual rates of induced emission and absorption as well as spontaneous photon emission [13]. The ionization efficiency is 0.73 for 100μJ of Lyman-α (1S to 2S) radiation and 300mJ ionization (2S to continuum) radiation.

4. Electrostatic acceleration

An SOa lens [14] are employed to accelerate the ultraslow 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 laser ionization region is between two mesh electrodes. The acceleration voltage of the lens is set to 5.6 keV corresponding to the RFQ input energy. The dimensions of the electrodes were designed to achieve enough extraction efficiency for ultraslow muons. The electrostatic field by the SOa lens is calculated by OPERA. Using the SOa electric-field and ultraslow muon distributions described in previous sections, the transmission efficiency is estimated by the GEANT4 simulation. Figure 6 shows typical result of particle tracking.

Figure 7 shows phase space distributions at entrance of the RFQ. The difference between the horizontal and vertical direction resulted from difference of the surface muon distributions. The transmission efficiency is estimated to be 72% including decay-loss of 17%. The transmission efficiency of the mesh electrodes was evaluated to be 78% by the mesh aperture ratio.

Red hatched line in Fig. 7 shows design acceptance of the RFQ. The transmission efficiency of the RFQ is estimated to be 81% including decay-loss [15] using PARMTEQM [16].
5. Summary
We have developed the simulation for H-line, Mu production, and electrostatic acceleration for the J-PARC \(g-2\) experiment. Table 1 summarizes efficiency and the muon intensity in each step. The muon intensity at entrance of the muon linac is estimated to be \(5.0 \times 10^5\) /s. The acceleration of the muon linac, injection to the storage magnet, and others can be found in \[15, \ 17, \ 18, \ 19, \ 20\]. We can investigate the \((g-2)_\mu\) anomaly with the same sensitivity to the previous experiment \[1\] with completely different method. Further developments for higher muon intensity are being conducted to achieve the target sensitivity.
Figure 7. Phase space distributions at entrance of the RFQ. Left is distribution for x and right for y. Red hatched line shows design acceptance of the RFQ.

| Step                          | Efficiency | Intensity (Hz) |
|-------------------------------|------------|----------------|
| $\mu^+$ at production target  | 0.16       | 2.0 x 10^{9}   |
| H-line transmission           | 0.16       | 3.2 x 10^{8}   |
| Mu emission                   | 3.8 x 10^{-3} | 1.2 x 10^{6}  |
| Laser ionization              | 0.73       | 9.0 x 10^{5}   |
| Metal mesh                    | 0.78       | 7.0 x 10^{5}   |
| USM transmission              | 0.72       | 5.0 x 10^{5}   |

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