COMMISSIONING OF THE DIAGNOSTIC BEAM LINE FOR THE MUON RF ACCELERATION WITH H⁻ ION BEAM DERIVED FROM THE ULTRAVIOLET LIGHT

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Abstract

A muon LINAC is under research and development for a precise measurement of muon $g-2/EDM$ at J-PARC. We conducted an experiment of a muon RF acceleration on October and December 2017. The surface muon beam is irradiated to a metal degrader to generate slow negative muonium. The slow negative muoniums are accelerated to 90 keV with an electrostatic accelerator and an RFQ. Prior to muon RF acceleration, we conducted a commissioning of the diagnostic beam line consisting of two quadrupole magnets and a bending magnet. The ultraviolet light is irradiated to an aluminum foil and H^- ion is generated. It simulates a negative muonium and is accelerated with an electrostatic accelerator. This system allowed us to check operation for the diagnostic beam line, which is essential task for transportation and momentum selection of the negative muonium. In this paper, I would like to report the performance evaluation of the diagnostic beam line by H^- ions.

INTRODUCTION

We are searching the signals of physics beyond the Standard Model through muon anomalous magnetic moment ($g-2$). The Standard Model of particle physics makes a very precise prediction of the muon $g-2$. An experiment (E821) at Brookhaven National Laboratory found a greater than three sigma discrepancy between the theoretical calculation and the measurement of the muon $g-2$ [1]. The discovery is expected to be an evidence of physics beyond the Standard Model. In the case of J-PARC E34, we plan to measure muon $g-2$ and EDM with new technique. We will provide a low emittance beam for high precision measurement by using a muon linac [2]. The surface muon beam [3] with a kinetic energy of 4 MeV from J-PARC material and life science experimental facility (MLF) is a large emittance beam since it is tertiary beams [4]. Therefore, cooling and reaccelerating muon beam are necessary to make a low emittance beam. First, surface muon beam is irradiated to a silica aerogel and forms muonium (Mu : bound state of μ^+ and e^- like light isotope of H). Muonium can be ionized by laser to produce the ultraslow muon with a kinetic energy of 25meV. Then the ultraslow muons are accelerated by a linear accelerator (linac) dedicated to muon. Therefore, muon acceleration with a radio-frequency (RF) accelerator is one of the element technology. We conducted an experiment of a muon RF acceleration on October and December 2017. The measured beam intensity of the accelerated Mu^- is $(5 \pm 1) \times 10^{-4}/sec$ [5], and It's very low. Thus, it is impossible to conduct the commissioning for the diagnostic beam line, which is composed of quadrupole magnets and a bending magnet, by using Mu^- beam. Prior to muon RF acceleration, we conducted the commissioning of the diagnostic beam line with H^- beam. The measured beam intensity of the accelerated H^- were $(7 \pm 2) \times 10^{-1}/sec$. The mass of H^- is different from the mass of Mu^-, although we can conduct the commissioning of magnets using H^- beam, which is identical with momentum for accelerated Mu^-. The paper reports the commissioning of the diagnostic beam line for the muon RF acceleration test.

EXPERIMENTAL SETUP

Figure1 shows the experimental setup [5]. First, the surface positive muon beam is provided from J-PARC MLF. Kinetic energy is about 4 MeV. Next is muon cooling. We did not use the laser dissociation method with silica aerogel target but metal degrader. The surface muon beam with 4 MeV is irradiated to a Kapton degrader and an aluminum foil to generate the slow Mu^-. The slow Mu^- is composed of the bound state of a μ^+ and two electrons. The slow Mu^- are accelerated to 5.6 keV with SOA lens, which is electrostatic accelerator [6]. To meet, the designed input energy of the radio frequency quadrupole linac (RFQ). Then, the 5.6 keV Mu^-'s are accelerated to 90 keV with an RFQ. As a diagnostic beam line, there are two quadrupole magnets and a bending magnet. Figure 2 shows the diagnostic beam line setup. Assuming the advancing direction of the Mu^- beam is Z axis, the Mu^- beam is focused in both X- and Y-direction with the quadrupole magnet pair. Moreover, beams are selected momentum with a bending magnet, which is located at the deflection line with an angle 45°. And, the bending magnet is effective to reducing backgrounds, which are composed μ^+ and proton. There are two detectors after

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a bending magnetic. One is located at the straight line to detect the penetrating positive muon, the other is located at the deflection line to detect the accelerated Mu⁻. The detector of the deflection line consists of a micro-channel-plate (MCP), a phosphor-plate, and a CCD camera. The CCD camera detects light signal from the phosphor-plate to measure the beam profile. The accelerated Mu⁻ is identified by measuring its TOF and its distribution [5]. During the commissioning period, the ultraviolet light is irradiated to an aluminum foil and H⁻ is generated. It simulates Mu⁻ and is accelerated at the same momentum of the accelerated Mu⁻ with only electrostatic accelerator. We used the optical instrument of xenon light source.

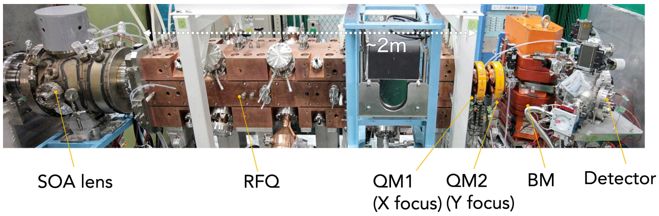


Figure 1: Experimental setup of muon RF acceleration test

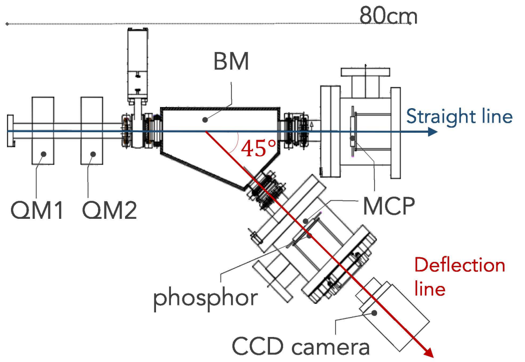


Figure 2: Schematic view of diagnostic beam line :There are two quadrupole magnets (QM1,QM2), and a banding magnet (BM), and MCP detectors at the straight line and the deflection line. The MCP, the phosphor, and the CCD camera of the deflection line is a beam profile monitor.

H⁻ Formation

There are two possibilities regarding H⁻ formation. The first possibility is the electron attachment processes. Negative ions are expected to be produced by dissociative attachment of electrons to vibrationally excited molecules [7]. Equation (1) shows that H_2 of ground state ($v = 0$) is excited to vibrational state ($v'' \gg 5$) by attachment of electrons, moreover photon ($h\nu$) is emitted too. Next, equation (2) shows that H⁻ is formed by attachment of electron, which is emitted by photoelectric effect, to vibrationally excited H_2.

$$H_2(v = 0) + e^- \rightarrow H_2(v'') + h\nu + e^- \tag{1}$$

$$H_2(v'') + e^- \rightarrow H^- + H \tag{2}$$

The second possibility is ion-pair formation process from super-excited states (SES) of H_2 as shown Eq (3) [8].

$$H_2 + h\nu \rightarrow H_2^{**} \tag{3}$$

SES means electronically excited states lying above the ionization energy [9]. Molecules are excited neutral excited state, when it absorbs more energy than the ionization energy by light excitation using ultraviolet light. The decay process of SES is several channels. Since SES exists discretely in the continuous state of ionization, electrons are emitted within a short period of time and are automatically ionized (Eq (4)). And, it is dissociated to neutral species and ion pairs, when molecular bond is weak (Eq (5), (6)). SES also decay a high Rydberg states, in which one electron has been excited into an orbital with a high principal quantum number [10] (Eq (7)).

$$\begin{aligned} H_2^{**} &\rightarrow H_2^+ + e^-(auto - ionization) && (4)\\ &\rightarrow H + H^*(n)(dissociation) && (5)\\ &\rightarrow H^+ + H^-(ion - pair formation) && (6)\\ &\rightarrow H_2^*(high - Rydberg - formation) && (7) \end{aligned}$$

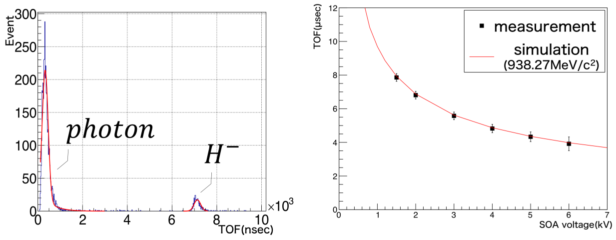
Equation (6) shows that H⁻ is formed by ion-pair formation. However, this process yields H⁻ with a lower efficiency than electron attachment to the vibrational states of H_2 [9]. Although we do not have a clear interpretation for H⁻ formation yet, it is likely to be due to an electron attachment process.

SIMULATION

The beam transport in the diagnostic line and TOF of H⁻ were simulated using as follow. The electrostatic acceleration by the SOA lens was simulated using the musrSim simulation [6]. The diagnostic line was simulated using software of TOSCA [11] and Geant4. TOSCA computes static magnetic fields in three dimensions from Maxwell's equations. The magnetic field data with TOSCA is imported to Geant4, which computes the tracking of particle.

RESULT

Figure 3(a) and 3(b) shows the identification of H⁻ by detecting the signal and the TOF distribution. Figure 3(a) shows the TOF distribution, which is detected two peak signals, when SOA lens is applied a voltage to 2 kV. Speculate that one is the photon, the other is H⁻. The peak signal of photon like by double-gaussian fitting is defined to the time zero. Moreover, we calculated the TOF of H⁻ like signal by using its peak signal by gaussian fitting. Figure 3(b) shows the plot, which is the acceleration voltage of SOA lens to the TOF of H⁻ like signal. The solid line shows the result of simulation with the particle having the same mass as H⁻. As a result, the measured TOF was consistent with the simulated TOF within the margin of error. Then, the charge of H⁻ like signal was identified the negative charge by bending it with a bending magnet. In conclusion, we have presented experimental evidence for the efficient formation of H⁻ with ultraviolet light irradiated to an aluminum foil. The measured beam intensity of H⁻ was $(7 \pm 2) \times 10^{-1}$/sec.

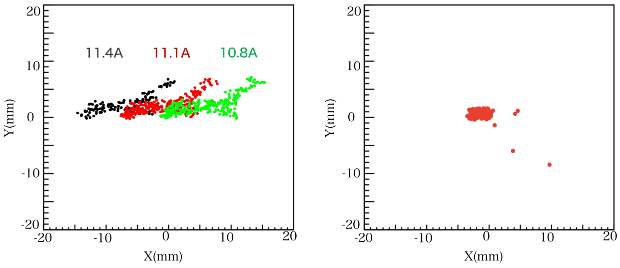


(a) (b)

Figure 3: Identification of H⁻ formation. (a) The measured TOF distribution of H⁻, when acceleration voltage is 2 kV. (b) Comparison of TOF gained from acceleration voltage between the measured data and simulation.

Commissioning

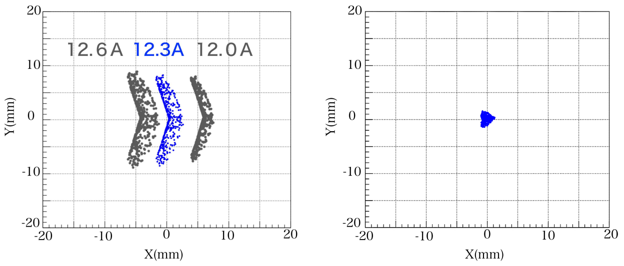
We measured the beam profile of H⁻ beam with the CCD camera. To fit the center beam axis with the central of the CCD camera screen, beam profile is measured by changing currents of a bending magnet as shown in Figure 4(a). As a result, H⁻ reaches the central of detector with 11.1 A, which was applied to the muon RF acceleration test. A bending angle is 0.5 degrees per 0.3 A. Figure 4(b) shows the beam profile, which is the optimum current value for quadrupole magnets. It has a diameter of approximately two to three millimeter, and is shaped like an ellipse, when the setting value of QM1 is 0.4 A and QM2 is 0.56 A. On the other hand, several signals were located at the distance from the beam axis. We consider that several signals were kicked by magnetic field of quadrupole magnets. Actually, these values were not applied to muon RF acceleration test, because, H⁻ beam have cross-section of the beam different from the accelerated Mu⁻. This experiment is necessary for us to check operation of quadrupole magnets.



(a) (b)

Figure 4: Beam profile measurement. (a)Fit the center beam axis with the central of CCD camera screen by using a bending magnet. (referred to as BM scan) (b)focus of H⁻ beam by using quadrupole magnets

Compare the measured current value and cross-section of beam with the simulation based on TOSCA and Geant4. Figure 5(a) and 5(b) shows the beam profile measurement, which is simulated in the same way as Fig. 4(a) and 4(b). The current value of a bending magnet is 12.3 A, when the central beam axis fits the central of CCD camera. The error in the measured current value is about ten percent. Speculate that the cause of error is that the effective length of a bending magnet for simulation is 15 percent less than the Design value. Moreover, the beam was focused, when the setting value of QM1 is 0.23 A and QM2 is 0.4 A. Although the simulation value is different from the measured value, this difference is within the error range. According to simulation, we assumed initial beam that all particles traveled horizontally with gaussian distribution. In contrast, initial beam of the commissioning has a widening angle. Therefore, the cause of error is difference of initial beam parameters.



(a) (b)

Figure 5: Beam profile simulation (a)BM scan(b)focus of beams by using quadrupole magnets

SUMMARY

We had completed preparing the diagnostic beam line, which is quadrupole magnets, a bending magnet, and MCP detector before we conducted muon RF acceleration test. We have conducted commissioning an experimental setup by using H⁻ beam derived from the ultraviolet light, although H⁻ formation and initial parameters have not been clarified. In the case of initial parameters, it is assumed that it is calculated from the measured beam profile and transfer matrix.

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