THE ACCELERATOR DESIGN OF MUON g-2 EXPERIMENT AT J-PARC

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Abstract

New muon g-2 experiment at J-PARC is aimed to conduct the precise measurement of anomalous magnetic moment (g-2) of the muons. In this experiment, the ultra-cold muons created in the muonium target region is reaccelerated to around 300 MeV/c in momentum (210 MeV kinetic energy) to then be injected into the muon g-2 storage ring to measure the decay products depending on the muon spin. The linac has advantage over circular accelerators to shorten the reacceleration time in the limited life time of muon. The muon linac consists of the initial acceleration (to 0.01 of v/c), bunching section (0.01 to 0.08 of v/c), low beta section (0.08 to 0.3 of v/c), middle beta section (0.3 to 0.7 of v/c) and high beta section (0.7 to 0.94 of v/c). As a part of the design consideration of this linac, we present the simulation result of initial acceleration and further acceleration of muons with RFQ. An electric field is used to extract the ultra-cold muons from the laser ionization region and RF field is used to create some bunches and to accelerate to higher energies.

INTRODUCTION

Japan Proton Accelerator Research Complex (J-PARC) consists of a 400 MeV linac, 3 GeV and 50 GeV synchrotron rings, which provide an intense proton beam to pursue particle and nuclear physics, materials and life science and nuclear technology. A 1 MW proton beam is transported from the 3 GeV synchrotron ring to Materials and Life Science Facility (MLF) which consists of the muon and the spallation neutron facilities. Fig. 1 shows the sketch of proton beamline tunnel which runs through the center of MLF building and muon production target associated with four muon beam transport lines. 1 MW proton beam injected to the target made of 20 mm thick, disc-shaped, isotropic graphite. About 5% of proton beam is consumed at the target. Pions are produced in sufficient numbers from collisions of high-energy protons with the nuclei of an intermediate target. Low energy muons are available in the required intensities only from ordinary two-body pion decay. Most positive muon beams are generated from pions stopped at inner surface layer of the primary production target and decaying at rest, hence the common name, surface muons. The muon is emitted isotropically from the pion with momentum 29.8 MeV/c and kinetic energy 4.119 MeV (in the rest frame of the pion). The intensity of surface muon beam can be estimated from the number of pions stopped near to the surface. As shown in Fig. 2 muon production target is built and four secondary beam transport lines are constructed. The extraction angle of two beam transport lines is 60 degrees to the proton beamline (forward) and the other two beamlines are extracted in 135 degrees to the proton beamline backward. Acceptance of beam transport line evaluated to be about 100 mstr, taking into account the extraction angle the effective surface-muon-emission rate is 15 000 M/s. Transported muon beam will be focused on tungsten target to produce muonium. Transmission efficiency of beamline is preferred to be as high as possible. The focused beam spot size is required to be less than 4 cm in diameter. Achieving the smallest beam spot size increases the slow muon beam intensity.

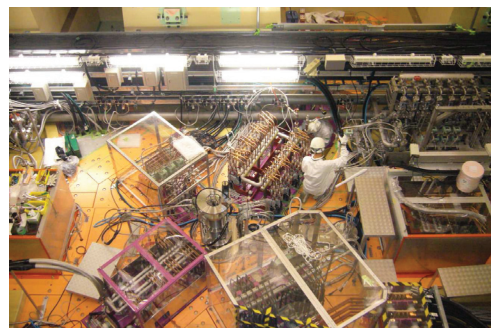

Figure 2: Muon production target associated with four muon beam transport lines.

MUON LINEAR ACCELERATOR

The muon accelerator consists of the initial acceleration (to 0.01 of v/c), bunching section (0.01 to 0.08 of v/c), low beta section (0.08 to 0.3 of v/c), middle beta section (0.3 to 0.7 of v/c) and high beta section (0.7 to 0.94 of v/c). Fig. 2 [1] displays the design of muon accelerator connected to beamline through muonium production target made of tungsten. The 29.8 MeV/c muon beam will be focused onto tungsten target to produce muonium (Mu), which is an exotic atom made up μ^+ and electron. The muonium is formed by electron capture of μ^+ near the surface of the hot tungsten foil. Then muonium atoms can be evaporated to the vacuum with thermal velocity. By producing muonium μ^+ beam will be effectively stopped, yet maintains its polarization. Thermal emission of muonium into a vacuum at target temperature of 2000 K proceeded with intense laser irradiation. The electrons are then stripped from the muonium atoms using two high-power new laser systems. One at wavelength of the muonium Lyman-α photo-excites the muonium from ground to $2P$ state, and then the other at wavelength of 366 nm ionizes the excited muonium. The ultra-cold muons produced this way will be fully polarized, with small transverse momen-

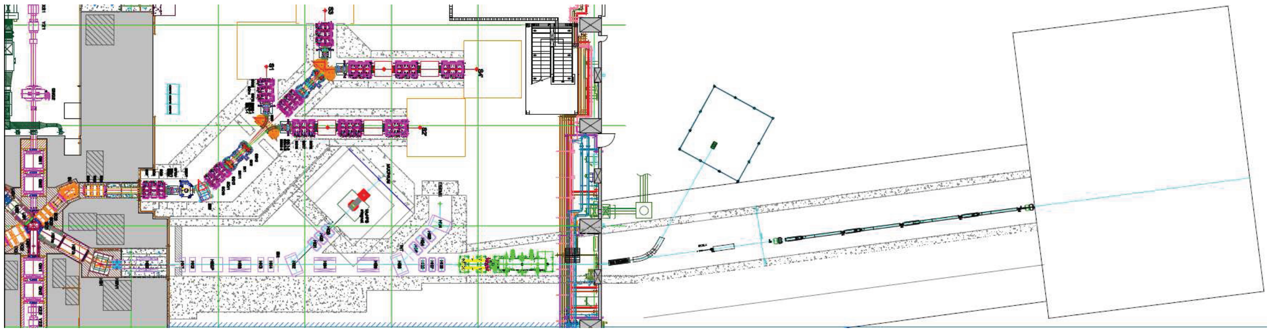

Figure 1: Top view of the muon production target and associated beam transport lines (J-PARC MLF). Two of these secondary beamlines are extracted at the angle of 60 degrees to the proton beamline (forward), and the others are at 135 degrees (backward).

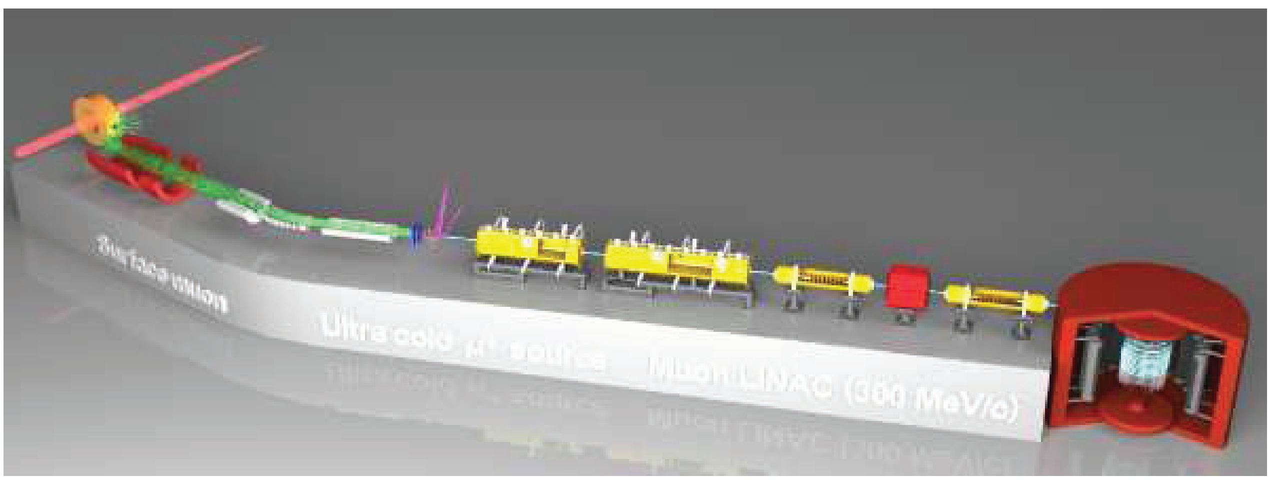

Figure 3: Design of muon linear accelerator.

tum. The thermalization process is the key point to cool down the muon beam. The baseline of muon accelerator is composed as follows

- ultra-cold muon extraction and initial acceleration with an electric field
- bunching and acceleration with a radio-frequency quadrupole (RFQ)
- low beta section employs inter-digital H-mode (I-H) structure
- middle beta section employs cut disk structure (CDS)
- high beta section employs disk loaded structure.

At the final energy of 210 MeV the muon beam will be injected into a storage field employing the spiral injection scheme where the g-2 experiment will be conducted.

Initial Acceleration of Cold Muons

Laser exposure is 5 mm away from tungsten target in z beam propagation direction with an area of 200 mm^2 for 1 ns at 0.6 μs after the second muon pulse (1.2 μs from the first muon pulse) corresponding to a coverage of muonium atoms emitted into vacuum to be 22%. The ionization efficiency of muonium atoms depends only on the laser intensity and can theoretically be as high as 100%, which would result in a total conversion efficiency of a few percent (starting from the surface muon). The energy spread as well as the divergence of the re-accelerated beam is much smaller than other methods of producing cold muons. Ultra-cold muons will be extracted from stripping region and accelerated, focused and matched into RFQ acceptance using an electric field generated by 5 electrodes in sequence, including the tungsten target. Corresponding voltages of electrodes are 5.66 kV, 5.62 kV, 5.35 kV, 3.41 kV, 0 V. Output transverse emittance of initial accelerated muons is estimated as 245 mm mrad and directly matched into RFQ acceptance of 247 mm mrad.

RFQ Acceleration Simulation Results

The designed longitudinal muonium bunch length is 5 mm and which much longer than the excitation laser pulse duration. Thus the bunching section is required to accelerate the muon beam using the RF accelerating structures. The spare RFQ from J-PARC LINAC will be utilized for test measurements of muon acceleration. We use existing RFQ design parameters as a baseline for simulation. Meanwhile, an RFQ is known to have a substantial nonlin-

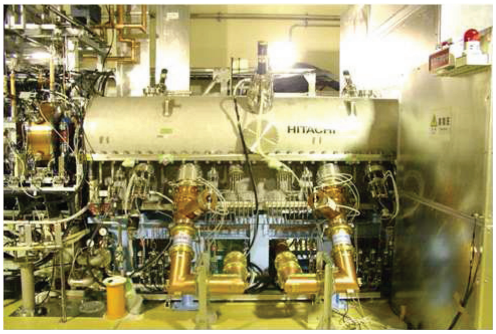

Figure 4: A radio-frequency quadrupole.

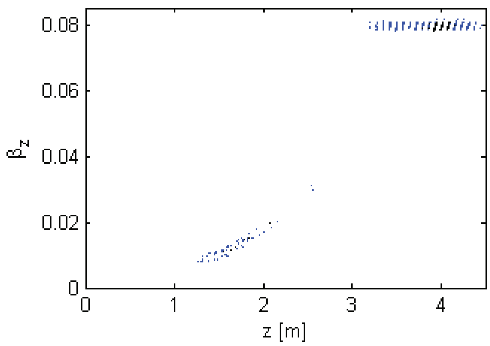

Figure 5: RFQ bunching and acceleration of the beam.

ear component of the RF field due to unavoidable deviation of its vane shape from the ideal one. Fig. 5 shows the result of the muon tracking through the RFQ with and without momentum spread. Total RFQ length is $z = 3.192$ m, output accelerated bunches correspond to normalized velocity of β_z =0.08. Bunches in blue color present muons having large momentum spread and bunches in black color shows the particles without momentum spread. Output bunches are shown in fig. 6 in which we estimated output transverse beam emittance as 33.14 mm mrad containing 90% particles in it. Summary of RFQ parameters are given in Table 1.

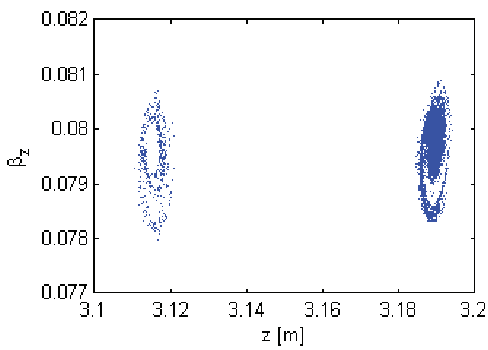

Figure 6: Accelerated bunches of the beam at RFQ output.

Table 1: (J-PARC) RFQ Parameters for μ^+

RF frequency	324	MHz
Normalized input velocity	0.0103	
Normalized output velocity	0.083	
Input kinetic energy	5.65	keV
Output kinetic energy	339	keV
Average bore radius	3.7	mm
Number of RFQ celles	284	
Output kinetic energy	339	keV
Intervane voltage	82.9	kV
Vane-tip curvature	3.293	mm
Radial matching section	2.86	cm
Shaper	55.14	cm
Gentle buncher	118.2	cm
Transition region	319.2	cm
Total RFQ length	319.2	cm

CONCLUSION AND OUTLOOK

Development and optimization of muon accelerator components are in progress. Existing J-PARC RFQ appears to be an adequate solution for 5.6 keV muon injection, especially if the input transverse emittance could be lowered. Consistency of simulation results are to be confirmed with the experimental measurements.

REFERENCES

[1] Conceptual design report for the measurement of the muon anomalous magnetic moment g-2 and electric dipole moment at J-PARC, December 13, 2011.