ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-THPF045

SIMULATION STUDY OF MUON ACCELERATION USING RFQ FOR A NEW MUON G-2 EXPERIMENT AT J-PARC

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Abstract

A new muon g-2 experiment is planned at J-PARC. In this experiment, ultra cold muons will be generated and accelerated using a linear accelerator. As the first accelerating structure, an RFQ will be used. We are planning to use a spare RFQ of the J-PARC linac for the first acceleration test. In this paper, simulation studies of this muon acceleration test are presented. A design study of a muon dedicated RFQ is also shown.

INTRODUCTION

The J-PARC E34 experiment aims to investigate particle physics beyond the standard model by measuring the muon anomalous magnetic moment (g-2) and the electric dipole moment (EDM) with precision of 0.1 ppm and $1 \times 10^{-21} e\cdot$cm, respectively [1]. E34 will be conducted at the H-line [2] of J-PARC muon science facility. This experiment needs a low-emittance muon beam, and to this end, the idea of reacceleration of cooled muon is utilized. The reacceleration of cooled muon is already proposed in [3], in which a wedge-shaped energy absorber is used to cool the muons. On the contrary, we are planning to use ultra cold muons (UCMs) generated by laser-ionization of thermal muoniums (Mu: μ^+e^-) form an silica-aerogel target [4]. Generated UCMs are accelerated using a muon linac. As the first step, a spare RFQ of J-PARC linac (RFQ II [5]) will be used as a front-end accelerator. The resonant frequency of RFQ II is 324 MHz.

Prior to construct the muon linac, we are planning to conduct a muon acceleration experiment using RFQ II at the H-line. The accelerated particle for E34 experiment is μ^+, however, the ultra cold muon source will not be available when the initial stage acceleration experiment will be performed. Therefore, we are developing a negative muonium (Mu^-) source [6], with witch the Mu^-'s are generated by decelerating the muons from the H-line using an aluminum degrader.

RFQ II is originally designed to accelerate H^-'s, and the mass of the $H^-$is nine times larger than that of muon. To accelerate muons using RFQ II, the power should be reduced to 1/80 of the design power; this is very inefficient. Therefore, we are planning to develop a muon dedicated RFQ (muRFQ), and replace RFQ II when the following accelerators are ready.

In this paper, simulation studies of muon acceleration using RFQs are described.

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UCM ACCELERATION USING J-PARC RFQ II

For the simulation of J-PARC RFQ II, PARMTEQM [7] is used because it was used for the optics design of RFQ II. To accelerate muons, the original input file should be modified as follows; 1) The particle mass is defined as muon. 2) Input and output energy are converted from the βs of the H^-. The muon mass and the input and output energy are summarized in Table 1 together with the original parameters for H^- acceleration.

Table 1: Parameter Conversion from H^- to μ

Beam species	H^-	μ
Mass (MeV/c^2)	939.302	105.658
Injection β	0.010318	
Injection energy (keV)	50.000	5.625
Extraction β	0.079732	
Extraction energy (MeV)	3.000	0.337
Inter vane voltage (V)	82.879	9.324
Nominal power (kW)	330	4.177

In this simulation, a particle distribution simulated using GEANT4 [6] is used, as shown in Fig. 1. The phase distribution is assumed to be uniform.

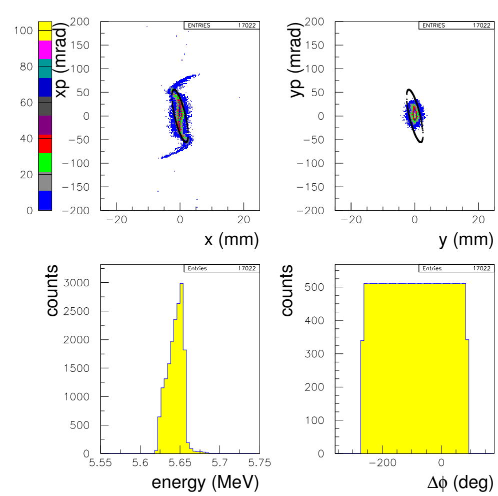

Figure 1: UCM distribution at the RFQ II entrance. The ellipses in upper figures represent the matched ellipses of $\varepsilon_{t,n,rms} = 0.167\pi$ mm mrad.

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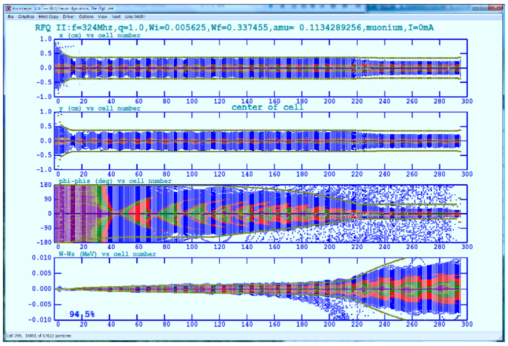

Figure 2: PARMTEQM simulation result of UCM acceleration.

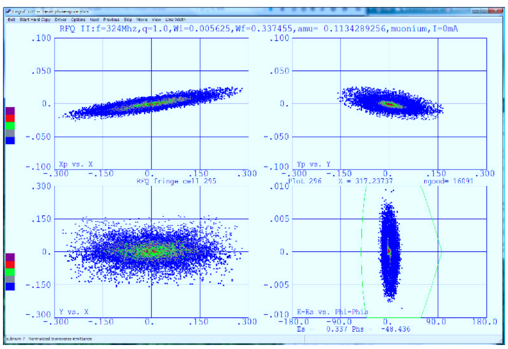

Figure 3: Particle distribution of muons at the RFQ II exit.

Figs 2 and 3 show the simulation results. The horizontal and vertical normalized rms emittances at the RFQ exit are 0.29 and 0.17 π mm mrad, respectively, and the energy spread is 3.4 keV. The simulated transmission is 94.5%. The number of the cells of RFQ II is 295, thus the transient time through the RFQ is 455 ns. Therefore the survival rate of the muon through the RFQ is estimated to be 0.81, and the total transmission is 77%.

SIMULATION OF MU⁻ ACCELERATION EXPERIMENT

The simulation for Mu⁻ acceleration experiment has been done also using PARMTEQM. Fig. 4 shows the particle distribution at the RFQ entrance simulated using GEANT4. In this experiment, the muons from the H-line are decelerated using an Al degrader, therefore, the transverse momentum of generated Mu⁻ is much larger than that of UCM case, thus the emittance at the RFQ entrance is very large. The phase distribution is also assumed to be uniform.

Fig. 5 represents the phase plots at the exit of the RFQ. The transmission through the RFQ is 9.5%, and the horizontal and vertical normalized rms emittances at the RFQ exit are 0.40 and 0.44 π mm mrad, respectively. Assuming the 1 MW proton beam is provided to the muon production target, the number of μ^+ on the Mu⁻ production target is estimated to be 3×10^6 /s. A conversion efficiency to Mu⁻ and the transportation efficiency are assumed to 1.8×10^{-4} [8] and 20%, respectively, therefore, the yield at the RFQ exit will be 8 Hz. To detect the accelerated Mu⁻ will be feasible with this rate.

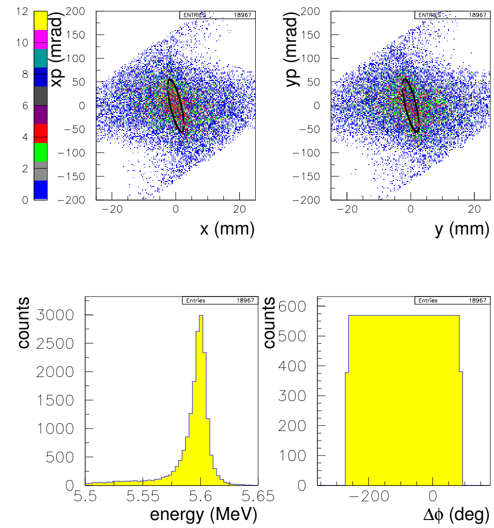

Figure 4: Input distribution of the Mu⁻ simulation.

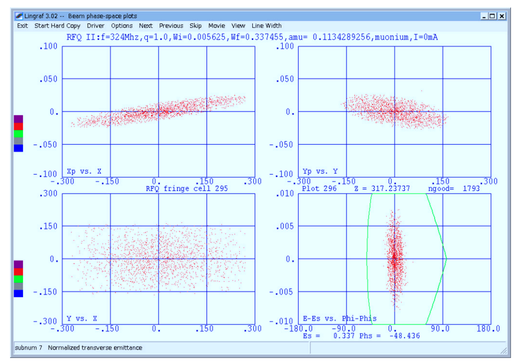

Figure 5: Phase plots of Mu⁻ at the RFQ exit.

MUON DEDICATED RFQ

In this section, preliminary design of muRFQ is shown. We used RFQGEN [9] for the beam dynamics design and the particle simulation of muRFQ. Fig. 6 shows the designed cell parameters of muRFQ.

To increase the acceleration efficiency, the inter-vane voltage is increased compared to that of RFQ II. Increased voltage makes the focusing force too strong, thus, the bore radius is also increased to reduce the focusing strength. In this design, the injection energy of muon is 30 keV and the extraction energy is 0.34 MeV.

Fig. 7 shows the evolution of the distribution trough the RFQ, and Fig. 8 represents the phase plots at the RFQ exit. The input transverse distribution for this simulation is 0.17 π mm mrad (normalized, rms) water-bag. As for the longitudinal distribution, no energy spread and uniform phase distribution are assumed.

In Table 2, the design parameters and the simulation results of muRFQ are summarized together with those of

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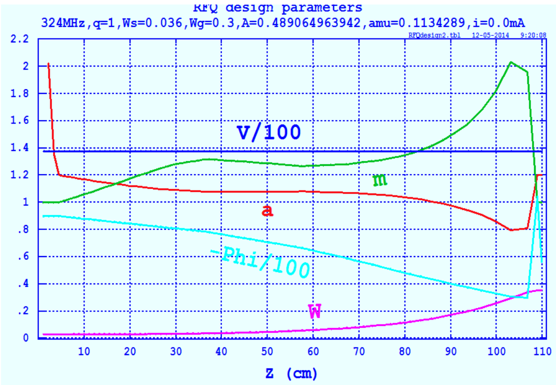

Figure 6: Designed cell parameters of the muRFQ using RFQGEN.

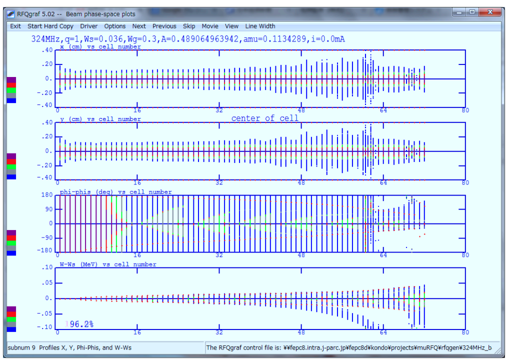

Figure 7: Evolution of the distribution in muRFQ.

RFQ II. As shown in Table 2, the vane length is 1/3 compared to RFQ II. Although the power dissipation is 50 times larger than that of RFQ II, it is a great merit because the fabrication of 1 m RFQ is much easier than that of 3 m RFQ. The number of cells is 72 and it takes 111 ns to pass through the RFQ. The transmission through the RFQ is 96%, it is a little bit lower than that of the RFQ, but the decay rate is improved from 20% to 5%, then the total efficiency is improved from 80% to 90%. The transverse emittance growth ratio of the present design is 20%, so it is necessary more optimization of the design.

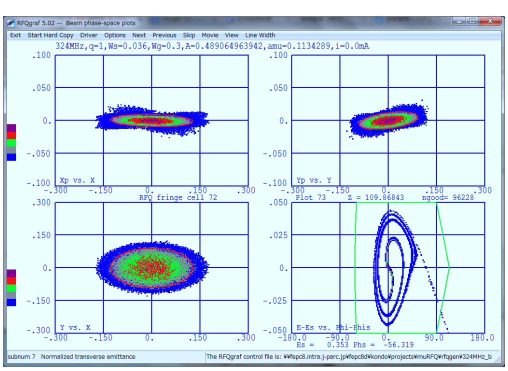

Figure 8: Phase plots of extracted particles from muRFQ.

Table 2: Design Parameters of RFQ II and Muon RFQ

	RFQ II	muRFQ
Resonant frequency (MHz)	324	
Injection energy (keV)	5.625	30
Extraction energy (MeV)	0.34	
Inter vane voltage (kV)	9.3	138
Power (kW)	4.2	200
Number of cells	295	72
Length (m)	3.17	1.10
Transmission (%)	99.9	96.2
Input emittance (π mm mrad, normalized, rms)	0.17	
Output emittance x (π mm mrad, normalized, rms)	0.17	0.20
Output emittance z (π MeV deg, rms)	0.021	0.25

SUMMARY

We performed simulation studies of RFQs for a new muon g-2 experiment at J-PARC. In the first phase of the experiment, J-PARC RFQ II will be used. A particle simulation of ultra-cold-muon acceleration using RFQ II has been done, and the transmission is 94.5%. Prior to the construction of the muon linac, a muonium acceleration test will be conducted. Simulation of the muonium acceleration is also done and the estimated muonium rate at the RFQ exit is 8 Hz. Design study of muon dedicated RFQ is going on, and we have demonstrated a compact 1-m muon RFQ design.

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