Development of Muon LINAC for the Muon g-2/EDM Experiment at J-PARC*

M. Otani, for the J-PARC E34 collaboration†
KEK, Tsukuba, Japan
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Abstract

We are developing a linac dedicated to the muon acceleration. It enables us to measure the muon anomalous magnetic moment with an accuracy of 0.1 ppm to explore beyond Standard Model of elementary particle physics. As a first step for demonstration of the muon acceleration, we are developing the source of slow muons with which RFQ acceleration is conducted. In order to cover the middle beta ($\beta \sim 0.3-0.7$) section of the muon LINAC, disk and washer coupled cell LINAC is employed and the DAW cell being designed now. This paper describes status of these developments.

INTRODUCTION

One of promising way to cast light on new physics beyond Standard Model is precise measurement of the muon anomalous magnetic moment $(g-2)_\mu$ in which there is a discrepancy between the SM prediction and measurement. The E34 experiment aims to measure $(g-2)_\mu$ with a precision of 0.1 ppm and search for EDM with a sensitivity to 10^{-21} e·cm by utilizing high intensity proton beam at J-PARC and newly developed novel technique of the ultra-cold muon beam.

We are developing a muon linac to accomplish the ultra-cold muon beam. First the thermal muon (30 meV) generated in the electric potential of 5.6 keV is injected to the radio-frequency quadruple (RFQ). The spare for the J-PARC LINAC RFQ, so called RFQ II, will be used for the muon LINAC. After RFQ, Interdigital H-type (IH) DTL will be used to accelerate muon from $\beta = 0.08$ to 0.27. Then disk and washer (DAW) coupled cavity is employed to $\beta = 0.7$ and then disk loaded structure accelerates muons up to 212 MeV/c.

As a demonstration of the muon acceleration, we are planning to accelerate muons with electro-static field and RFQ II. Next section describes development of the muon source and RFQ for that test. Following section shows current status of the following RF cavity design, especially for DAW.

MUON ACCELERATION WITH RFQ

In order to conduct muon acceleration with RFQ, slow muon source is being developed. One of the promising candidates is negative muonium ($\mu^+e^-e^-$, Mu$^-$) or slow muon emission by injecting the surface muon beam to a thin metal foil. Previous experiment observed Mu$^-$ and slow muon emission from an Al foil with average energy of 0.2 ± 0.1 keV and few keV, respectively, which can be injected to the RFQ II whose injection energy is 5.6 keV.

The measurement of the Mu$^-$ or slow muon emission efficiency and its kinematics was proposed and approved in J-PARC MLF. Figure 1 shows the experimental setup of the measurement. Surface muons are injected into the Mu$^-$ production target. The emitted Mu$^-$ is accelerated and focused by the electro-static lens and transported to the detector chamber by following electro-static quadrupoles and electro-static deflector. The Micro-Channel-Plate (MCP) is used for counting and timing measurement of Mu$^-$ and surrounding plastic scintillators for the decay-positron detection.

Figure 2 shows expected MCP timing distribution estimated by the GEANT4 simulation. In the simulation, the Mu$^-$ signals are generated at the Mu$^-$ target with kinetic energy of 0.2 keV and beam related backgrounds are estimated by injecting the beam muons towards the target. Backgrounds mainly consist of decay-positrons from the beam muons stopped around the target and the deflector, which can be reduced effectively by lead shields around the target chamber and the collimator located on downstream of the deflector. The signal to background ratio is estimated to be more than ten and clear separation between these can be achieved by observed timing as shown in Fig. 2.

The slow muon beamline has been assembled in J-PARC MLF. It was originally developed and operated in RIKEN-RAL port-3. It successfully demonstrated transportation of the slow muon beam. After shutdown of the beamline, some of the beamline components were moved to J-PARC for the Mu$^-$ measurement in summer 2014. Assembly and commissioning of all the equipments were completed by May 2015. Figure 3 shows one of the commissioning results of the beamline; an Al plate installed at the Mu$^-$ target holder location is irradiated by UV light and then generated photo-electrons are accelerated and transported to the MCP detector location. The photo-electron events are observed successfully with nominal setup of the beamline components. Though current setup for Mu$^-$ suffers background due to the field emission electrons from the electro-static lens electrodes, the setup for slow muon setup can be operated stably. Upgrade such as a magnetic equipment installation to separate the field emission electron from Mu$^-$ is being discussed.

In conclusion, all the equipments are ready for slow muon measurement.

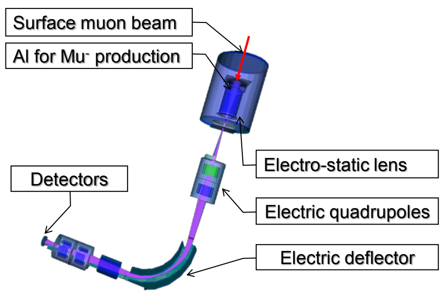

FIG. 1: Experimental setup for the Mu$^-$ emission measurement at the J-PARC MLF muon beamline.

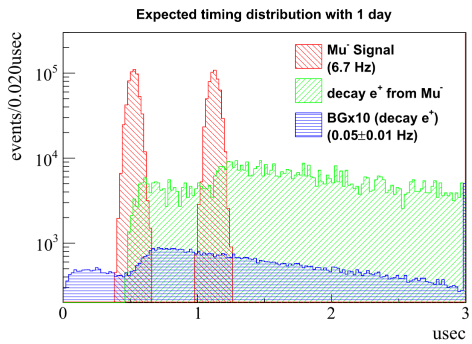

FIG. 2: Expected timing distribution estimated by the GEANT4 simulation.

In order to verify the RFQ II operation and measure the background from the RF field with MCP, the RFQ offline test was performed in June 2015 in the J-PARC LINAC building. Figure 4 shows photo of the RFQ offline test setup. The MCP detector chamber is connected to the RFQ downstream. Vacuuming is done with an ion pump and reach 10^{-6} Pa. The RFQ is powered on by low RF source and solid state amplifier up to 6 kW and 25 Hz repetition. The forward, reflection waves and RFQ internal power are monitored by power meters.

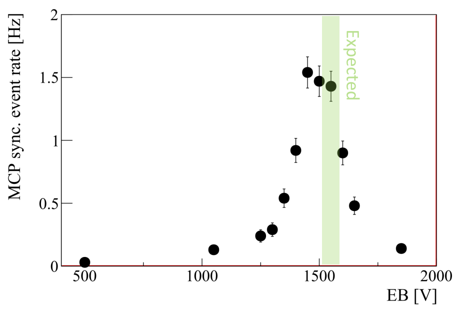

FIG. 3: Result of the beamline commissioning.

FIG. 4: Photo of the RFQ offline test at the J-PARC LINAC building.

Figure 5 shows the forward, reflection and pick-up power in RFQ with nominal power (5 kW) operation. Rising time is well consistent with expectation from Q factor. Figure 6 shows result of the MCP background measurement. Because the slow muon beam intensity in the first stage of the acceleration test is expected to be several counts per second, it is necessary to measure background level with comparable accuracy to that. Though it was expected that there might be background events due to electron or X-ray excited by RF field, all the measurements are consistent each other within statistical error of about 0.1 Hz and no background events are observed.

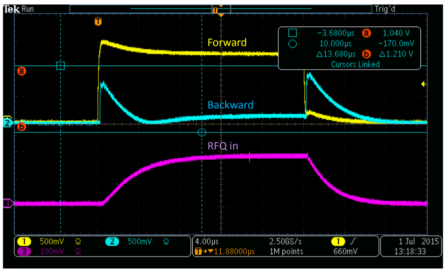

FIG. 5: Forward, reflection wave and pick-up power in RFQ with nominal power of 5 kW.

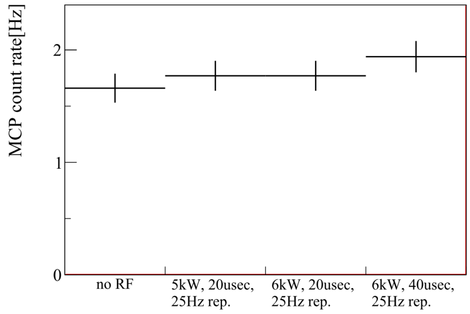

FIG. 6: Result of the MCP background measurement. All the measurements are consistent each other within statistical error.

In conclusion, RFQ is successfully operated and accelerated muons can be measured by MCP without beam related background.

DEVELOPMENT OF THE MIDDLE β SECTION

In the middle beta section ($\beta = 0.3 \sim 0.7$), the DAW cavity will be employed. It has high effective shunt impedance and high degree of coupling between adjacent RF cells. In order to solve the mode overlapping problem, a bi-periodic L-support structure is employed.

It is necessary to design our DAW cavity because muon acceleration is the first time in the world and the DAW cavity covering such a wide range of velocity is also the first time. In order to achieve higher acceleration gradient, the cavity design is optimized as follows. First, two dimensional model without the washer supports is optimized by calculating acceleration and coupling mode with SUPERFISH. Variable parameters are disk radius ($\mathrm{T_d}$), disk thickness ($\mathrm{T_d}$), washer radius ($\mathrm{R_w}$) and gap between washer (G). Optimization process is done by the SIMPLEX algorithm and the optimization function is constructed with confluent condition ($f_a = f_b$), higher shunt impedance (ZTT), and uniformity of the acceleration field. After optimization in two dimensional model three dimensional model with the washer supports is constructed based on the optimized dimensions with the 2-D code, with which resonant modes around operation frequency of 1.3 GHz are calculated in CST MICROWAVE STUDIO. Here the connection radius of the supports is decided to be the zero-electric point to minimize perturbation to the accelerating mode. In addition, the disk radius with and without the supports are slightly modified to recover the periodic feature of the acceleration field. The three dimensional model is also optimized by using same optimization function as two dimensional one. Finally the dispersion curve is investigated to check whether unfavored mode exists or not around the operation frequency. All the steps are repeated in several cavity lengths of $\beta\lambda/4$.

Figure 7, Fig. 8 and Tab. I show the dispersion curve, optimized model and optimized parameters, respectively, with $\beta = 0.3, 0.4, 0.5$ and 0.6. Because of bi-periodic structure, some stop bands appear in $\pi/2$. Though TM11 mode is near to the operational frequency, the cavity is tuned in the optimization process so that the operational frequencies sit in the stop band at $\pi/2$. Though the dipole mode passband TE11 crossed the line where the phase velocity matches the speed of muons, it is considered to be no problem because the muon beam current is negligibly small and transverse kick due to this mode is estimated to be much smaller than our requirement.

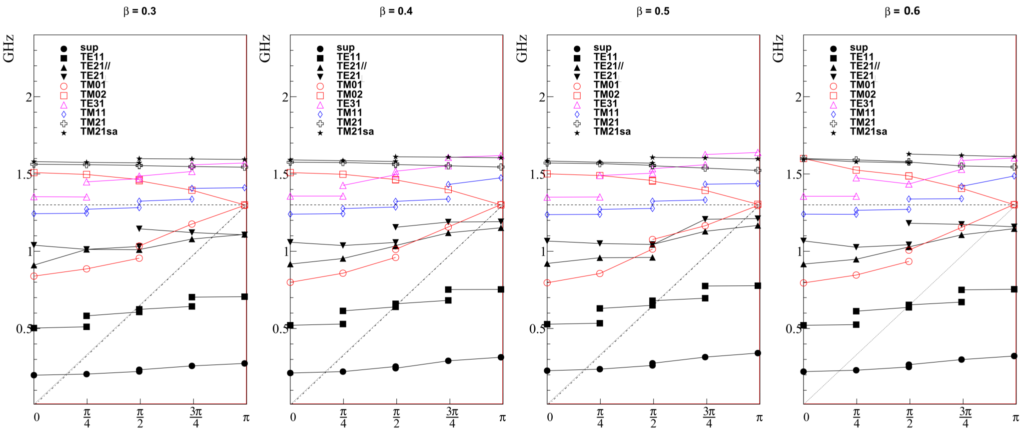

FIG. 7: Dispersion curve with optimized cavity in several β calculated by CST MICROWAVE STDUIO.

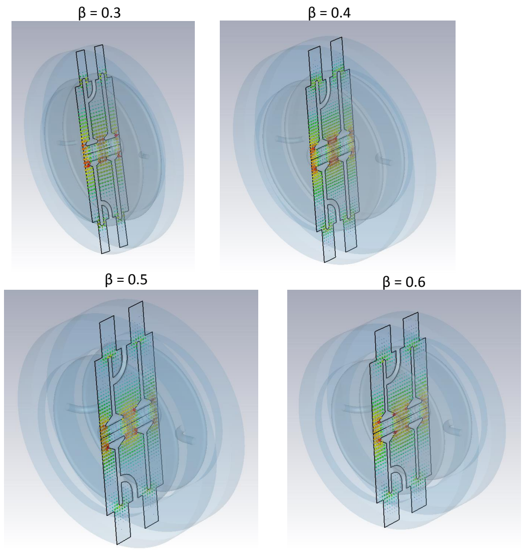

FIG. 8: Optimized three dimensional models in CST MICROWAVE STUDIO.

TABLE I: Parameters of the optimized DAW cavity.

β	0.6	0.5	0.4	0.3
L		$\beta\lambda/4$		
R_b[mm]		12		
R_n[mm]		2.6		
T_w[mm]		3.5		
θ[deg.]		30		
R_c[mm]	155	157	154	151
R_d[mm]	111.3	108.352	104.52	103.221
T_d[mm]	16.014	14.790	10.97	9.630
R_w[mm]	105.969	105.63	108.14	110.391
G[mm]	15.975	11.285	7.8976	6.148
f_a[GHz]	1.300	1.300	1.299	1.301
f_c[GHz]	1.299	1.301	1.302	1.301
ZTT[MΩ/m]	57.8	46.3	33.8	18.0

In conclusion, we completed design of the DAW cavity based on computer calculator. We are planning to fabricate a cold model made for measurement such as resonant frequencies.

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† `masashio@post.kek.jp`; Speaker