DEVELOPMENT OF MUON LINAC FOR THE MUON G-2/EDM EXPERIMENT AT J-PARC

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Abstract

We are developing a linac dedicated to the muon acceleration for the muon g-2/EDM experiment at J-PARC. This paper describes development status.

INTRODUCTION

Though the 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.

At present, we are developing a muon linac for the $(g-2)_\mu$ experiment at the Japan Proton Accelerator Research Complex (J-PARC) [2], in order to realize a low-emittance muon beam. In the experiment, ultra slow muons with an extremely small transverse momentum of 3 keV/c (kinetic energy W = 30 meV) are generated via thermal muonium production [3] followed by laser dissociation [4]. The generated ultra slow muons are electro-statically accelerated to $\beta = v/c = 0.01$ (5.6 keV) and injected into the muon linac.

Figure 1 shows the muon linac configuration. In order to obtain a longitudinally bunched beam, a radio-frequency-quadrupole (RFQ) accelerator is employed for the first-stage acceleration. The operational frequency is chosen to be 324 MHz, in order to optimize the experiences at the J-PARC H^- RFQ [5]. Although conventional linacs adopt Alvarez DTLs after RFQs, an H-mode DTL is employed during the particle velocity β = 0.08 to 0.28 (4.5 MeV) stage, so as to yield a higher acceleration efficiency. After the muon is accelerated to β = 0.28, a disk-and-washer (DAW) -type coupled cavity linac (CCL) with an operational frequency of 1.3 GHz is employed for effective acceleration [6]. Because the β variation is modest in the high-β region, the design emphasis has been shifted to achieving a high accelerating gradient, in order to realize a sufficiently short distance. Therefore, a disk-loaded structure is used for β is greater than 0.7 (42 MeV).

This paper describes developments status of electro-static acceleration, RFQ, and DAW. Other developments can be found elsewhere [7, 8].

ELECTRO-STATIC LENS

The ultra slow muons are accelerated and injected into the RFQ by the electro-static lens, so called SOA lens. In February 2016, the equipments were commissioned at the J-PARC muon beam facility with deceleration scheme by thin metal foil [9]. Figure 2 shows the experimental setup of the commissioning. The conventional surface muon beam injected to thin metal foil and the decelerated muons are accelerated by the SOA lens. Then the muons are transported by the electro-static components and detected by the detector system that consists of the microchannel plate (MCP) [10] and surrounded scintillator for decay positron detection. The details of the equipments and detectors can be found in [11].

Figure 3 shows the event timing distribution observed by the MCP detector. The dominant peak observed at ∼ 2.8 μsec is considered to be proton events that were attached on and knocked out from surface of the thin metal foil. The pre-dominant peak observed at ∼ 0.8 μsec is muon events, as the time of flight and the MCP pulse height distribution are matched to those of muons. We succeeded to decelerate the muons with thin meal foil and accelerate the muons by the SOA lens.

RFQ

The spare for the J-PARCLINAC RFQ, so called RFQII [12],will be used for the muon LINAC. 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.

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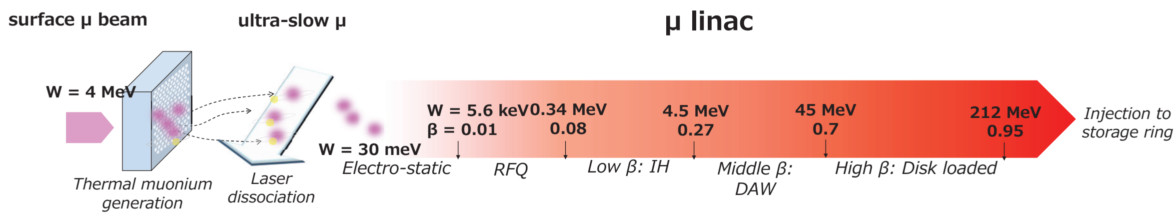

Figure 1: Configuration of low-emittance muon beam.

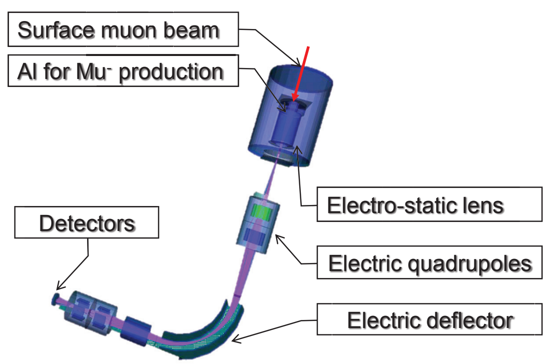

Figure 2: Setup of the SOA lens commissioning.

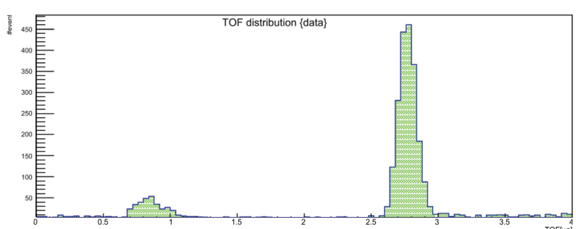

Figure 3: Event timing distribution observed by the MCP detector.

Figure 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.

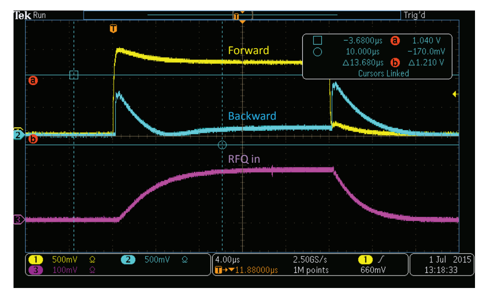

Figure 5: Forward, reflection wave and pick-up power in RFQ with nominal power of 5 kW.

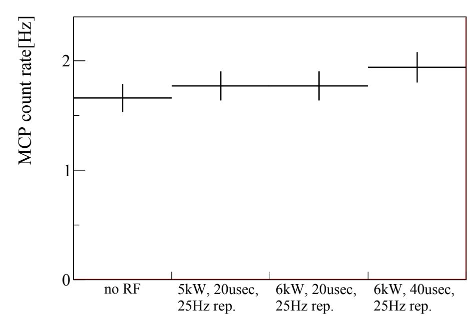

Figure 6: Result of the MCP background measurement. All the measurements are consistent each other within statistical error.

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

DAW

In the middle beta section ($\beta = 0.3 \sim 0.7$), the DAW cavity will be employed [13]. 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 [14].

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 as shown in Fig. 7 is optimized by calculating acceleration and coupling mode with SUPERFISH. Variable parameters are disk radius (T_d), disk thickness (T_d), washer radius (R_w) and gap between washer (G) as shown in red characters in Fig. 7. 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 $\beta\lambda/4$.

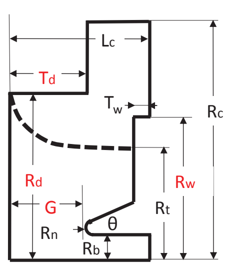

Figure 7: Two dimensional model of the DAW cavity and notations of the dimensions. Red characters are variable parameters in the optimization process.

Figure 8 and Table 1 show the dispersion curve, optimized model and optimized parameters, respectively. 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.

Based on the optimized DAW cell model, a cold model fabricated in Al was desiend as shown in Fig. 9. The model is being assembled and will be tested soon.

In conclusion, we completed design of the DAW cavity based on computer calculation and will test the cold model soon.

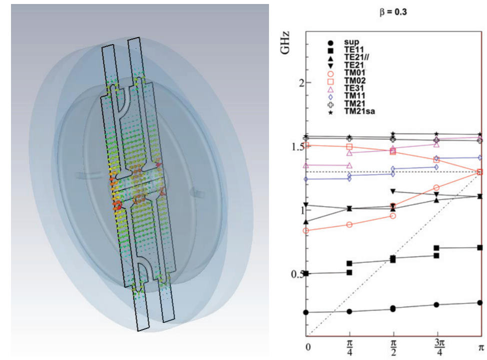

Figure 8: Dispersion curve with optimized cavity in several β calculated by CST MICROWAVE STDUIO.

Table 1: 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

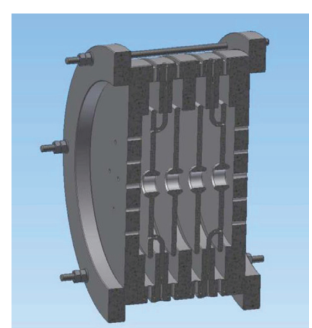

Figure 9: Design of DAW cell cold model.

SUMMARY

Muon acceleration is required for precision measurement of $(g-2)_\mu$ with the low-emittance muon beam. We are ready for muon acceleration with RFQ, which will be first case in the world. As long as new muon beamline at J-PARC MLF (H-line) [15] is constructed, the muon acceleration will be demostrated. Design of the DAW cavity has been completed and cold model measurement is planned.

ACKNOWLEDGMENT

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