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THE MUON LINAC PROJECT AT J-PARC

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Abstract

The muon linac project for the precise measurement of the muon anomalous magnetic and electric dipole moments, which is currently one of the hottest issues of the elementary particle physics, is in progress at J-PARC. The muons from the J-PARC muon facility are once cooled to room temperature, then accelerated up to 212 MeV with a normalized emittance of 1.5 pi mm mrad and a momentum spread of 0.1%. Four types of accelerating structures are adopted to obtain the efficient acceleration with a wide beta range from 0.01 to 0.94. The project is moving into the construction phase. We already demonstrated the re-acceleration scheme of the decelerated muons using a 324-MHz RFQ in 2017. The high-power test of the 324-MHz Interdigital H-mode (IH) DTL using a prototype cavity has been performed in 2021. The fabrication of the first module of 14 modules of the 1296-MHz Disk and Washer (DAW) CCL will be done to confirm the production process. Moreover, the design work of the traveling wave accelerating structure for the high beta region has almost finished and prototyping is started. In this paper, the recent progress toward the realization of the world first muon linac will be presented.

INTRODUCTION

The muon anomalous magnetic moment $(g-2)_\mu$ is one of the most promising probe to explore the elementary particle physics beyond the standard model (SM). The most recent experiment FNAL E989 measured the $(g-2)_\mu$ with a precision of 0.46 ppm, and the measured value indicates 4.2 standard deviations from the SM prediction [1]. The J-PARC E34 experiment aims to measure the $(g-2)_\mu$ with a precision of 0.1 ppm. In addition, the electric dipole moment (EDM) also can be measured with a precision of $1 \times 10^{-21} e{\cdot}\mathrm{cm}$ [2]. Figure 1 shows the experimental setup of J-PARC E34.

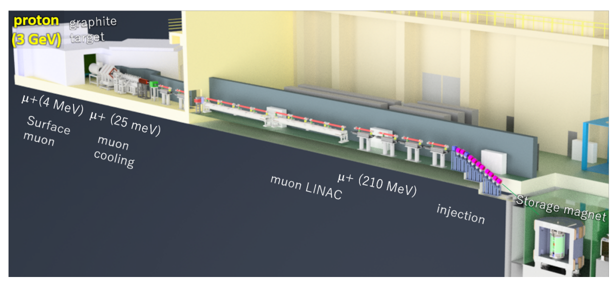

Figure 1: Experimental setup of the J-PARC E34 experiment.

The experimental method of E34 is completely different from that of the previous experiments. The previous experiments directory used decay muons from the secondary pions generated on the production target. The emittance of such muon beam is very large (typically, 1000π mm mrad); this is a major source of uncertainty of the measurement. On the other hand, E34 will use a low emittance muon beam to improve the precision. The required beam divergence $\Delta p_t/p$ is less than 10^{-5}, and assumed transverse emittance is 1.5π mm mrad. To satisfy this requirement, we are planning to use ultra-slow muons (USMs) generated by laser-dissociation of thermal muoniums (Mu: μ^+e^-) form a silica-aerogel target [3]. The room temperature USMs (25 meV) should be accelerated to 212 MeV to obtain the required

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$\Delta p_t/p$. A linac realizes rapid acceleration required to accelerate muons, whose lifetime is very short (2.2 µs). Figure 2 shows the configuration of the muon linac, and table 1 summarizes the main parameters of the muon linac.

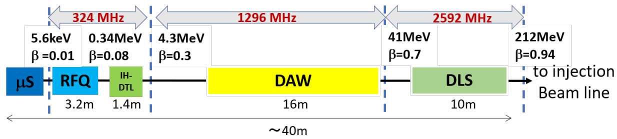

Figure 2: Configuration of the muon linac.

Table 1: Main Parameters of the Muon Linac

Particle	μ^+
Energy	212 MeV
Beam intensity	1×10^6 /s
Repetition rate	25 Hz
Beam pulse width	10 ns
Normalized transverse emittance	1.5π mm mrad
Momentum spread	0.1%

The muon linac will be constructed at the H line [4] of the J-PARC muon science facility (MUSE). The MUSE facility is a part of the J-PARC Materials and Life science experimental Facility (MLF). The USMs are bunched and accelerated to 0.34 MeV by a radio frequency quadrupole linac (RFQ) [5]. Following the RFQ, an interdigital H-mode drift tube linac (IH-DTL) [6] is used to accelerate to 4.26 MeV. Then, muons are accelerated to 41.4 MeV through a disk and washer (DAW) coupled cavity linac section [7], and finally, accelerated to 212 MeV using disk loaded traveling wave structures (DLS) [8]. The first beam will come to the first experimental area of the H-line in the existing MLF building in this year. The muon linac will be installed in a new building extended outside the current MLF building.

In this paper, the present status of the development of the muon linac is described.

RFQ

To reduce the construction cost of the muon linac, existing spare RFQ of the J-PARC linac (RFQ II) [9] will be used. In table 2, the main parameters of the RFQ are listed, and Fig. 3 shows the photograph of the RFQ II. The resonant frequency of this RFQ is 324 MHz, and the muons are accelerated to 0.34 MeV.

We demonstrated muon re-acceleration scheme by using epithermal negative muoniums (Mu$^-$; $\mu^+e^-e^-$) and a test RFQ in 2017 [10]. Figure 4 shows the TOF spectra with and without the RF operation. With the RF operation, a clear peak was observed at 830 ns. This is consistent with the estimated TOF of the accelerated Mu$^-$ up to 89 keV obtained by the simulation. The design output energy of this test RFQ for muon acceleration is 89 keV. The hatched histogram in Fig. 4 represents the simulated TOF spectrum of the accelerated Mu$^-$.

Table 2: Main Parameters of the RFQ

Structure	four-vane RFQ
Operation frequency	324 MHz
Injection energy	5.63 keV
Extraction Energy	0.337 MeV
Vane length	3.172 m
Number of the cells	294
Average bore radius r_0	3.69 mm
Min. bore radius a_{min}	2.11 mm
Max. modulation factor m_{max}	2.28
Max. synchronous phase $\phi_{s,max}$	-30 deg
Intervane voltage	9.32 kV
Maximum surface field	3.56 MV/m (0.2 E_k[1])
Nominal power	4.18 kW

[1]Kilpatrick limit

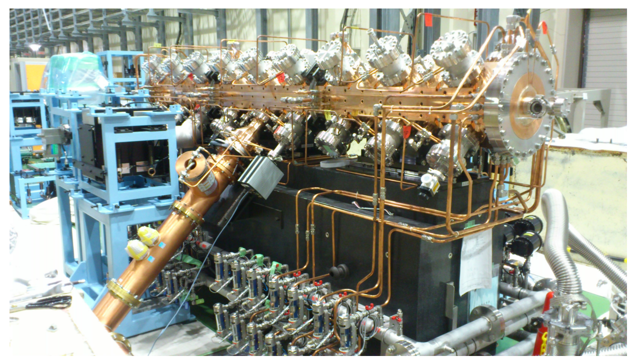

Figure 3: Photo of J-PARC RFQ II.

IH-DTL

The IH-DTL is used to accelerate the muons from the RFQ exit to 4.26 MeV [6]. Table 3 shows the main parameter of the IH-DTL.

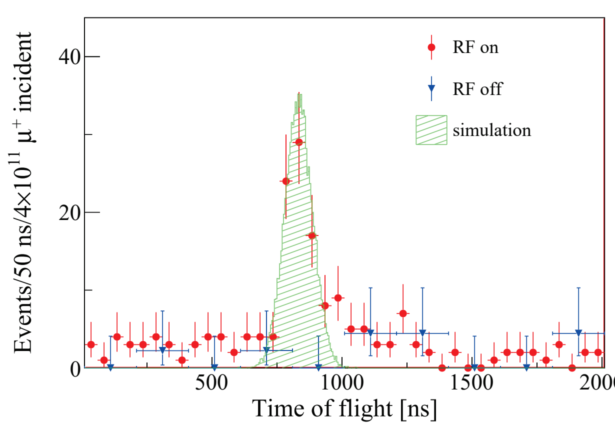

Figure 4: TOF spectra with RF on and off. The clear peak of the RF on spectrum at 830 ns corresponds to the accelerated Mu$^-$'s. A simulated TOF spectrum of the accelerated Mu$^-$'s is also plotted.

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Table 3: Main Parameters of the IH-DTL

Structure	APF IH-DTL
Operation frequency	324 MHz
Operation mode	π
Injection energy	0.337 MeV
Extraction Energy	4.26 MeV
Cavity length	1.32 m
Number of the cells	16
Bore radius	11.4 mm
Synchronous phase ϕ_s	-44 ~ 48 deg
Max. accelerating gradient E_0	10 MV/m
Effective shunt impedance ZTT	68 MΩ/m
Maximum surface field	35.6 MV/m (2.0 E_k)
Nominal power	310 kW

Alternative phase focusing (APF) is adopted for this IH-DTL to omit focusing magnets in the drift tubes. Figure 5 shows the synchronous phase array to realize the APF [11].

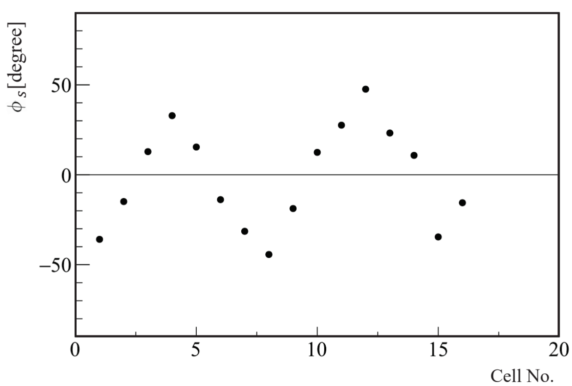

Figure 5: Synchronous phase array of the APF-IH.

One of the major merit of the APF IH-DTL is that the drift tubes can be machined as a monolithic structure. Figure 6 shows the structure of the IH-DTL. The cavity is formed by attaching half cylinder structures to both sides of this center plate.

High-power test using a prototype cavity, which is basically the same structure but have only six cells, has been performed, as shown in Fig. 7. This prototype IH-DTL can accelerate muons to 1.3 MeV. The robustness of the structural concept of the IH-DTL cavity we adopted has been verified by this high-power test. The detailed results are described in the separated paper [12].

The fabrication of the IH-DTL production model has been completed. It is ready for installation, and the beam test is planed in 2024.

DAW

After the IH-DTL, muons are accelerated to 41.4 MeV through the DAW section [7]. Table 4 shows the main parameter of the DAW section. The acceleration frequency is increased to 1296 MHz and the accelerating gradient E_0 is

Figure 6: Cavity structure of the IH-DTL. DT's are monolithically machined in the center plate

Figure 7: High-power test of the prototype IH.

5.6 MV/m. Single DAW tank consists of 11 cells, as shown in Fig. 8. And four or five tanks are connected with a coaxial bridge couplers to form a module. In the bridge coupler, a quadrupole doublet is contained. The length of one focusing period is 4.5 $\beta\lambda$. The DAW section consists of 3 modules, and each module is driven by one 2.5 MW klystron.

The assembly of the first tank is now underway. Figure 9 shows assembling the first cell. The washers are attached to the outer cavity (disk) via the stems made of Cu plated stainless steel by two-step brazing. Cooling water is supplied to the washers through the stems. Assembled single sells will be brazed to be a tank after the frequency tuning of each cell. The first tank will be completed within this fiscal year.

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Table 4: Main Parameters of the DAW section

Cavity structure	DAW CCL
Operation frequency	1296 MHz
Operation mode	$\pi/2$
Injection energy	4.26 MeV
Extraction Energy	41.4 MeV
Section length	16.15 m
Number of tanks	14
Number of modules	3
Number of tanks / module	4, 5, 5
Number of cells / tank	11
Number of quadrupoles	26
Bore radius	12 mm
Synchronous phase ϕ_s	-30 deg
Accelerating gradient E_0	5.6 MV/m
Effective shunt impedance ZTT	18.6 ~ 62.7 MΩ/m
Maximum surface field	28.9 MV/m (0.9 E_k)
Max. power / tank	420 kW

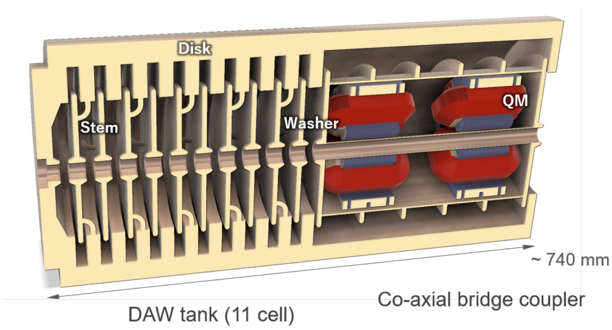

Figure 8: Structure of the DAW single tank and a coaxial bridge coupler.

DLS

Above 40 MeV, the velocity β of the muon is more than 0.7; therefore, a disk-loaded structure (DLS) traveling-wave (TW) linac is applicable. The DLS TW structure is quite mature technique widely used for electron linacs. However, because the velocity evolution of the muon is slower than that of the electron, the length D of each cell is synchronized to the velocity as $D = \beta_s\lambda/3$, where β_s is the velocity of the synchronous particle and λ is the wavelength of the RF. Namely, $2\pi/3$ mode operation is adopted. The operation frequency of the original design was 1296 MHz [13], however it was changed to 2592 MHz to decrease the required power [8]. In table 5, the main parameters of the DLS are summarized. The expected E_0 is around 20 MV/m.

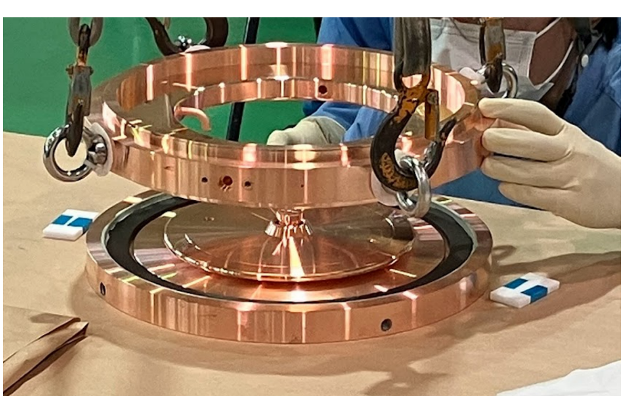

Figure 9: Assembling the DAW first cell.

Table 5: Main Parameters of the DLS

Accelerating tube structure	Disk-loaded TW
Operation frequency	2592 MHz
Operation mode	$2\pi/3$
Injection energy	41.4 MeV
Extraction Energy	212.4 MeV
Section length	9.8 m
Number of accelerating tubes	4
Number of cells / tubes[1]	63, 63, 60, 60
Iris aperture diameter $2a$	22.6 ~ 26.4 mm
Synchronous phase ϕ_s	-13 deg
Max. accelerating gradient E_0	21 MV/m
Shunt impedance Z	31.2 ~ 57.0 MΩ/m
Max. power / tube	40 MW

[1] excluding coupler cells

Figure 10 represents the cell parameters of the DLS. Constant gradient structure is adopted, so the iris diameter $2a$ is varied with respect to z.

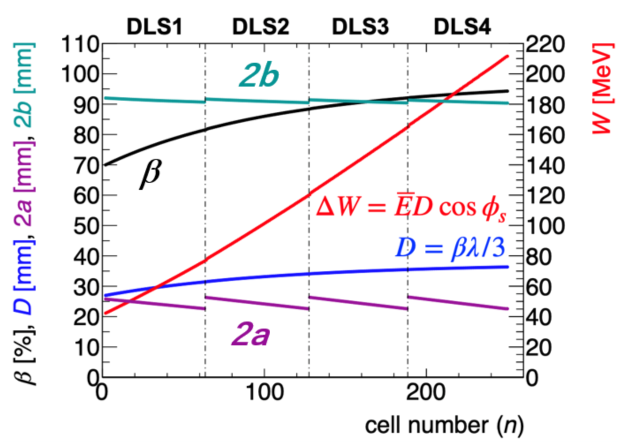

Figure 10: Cell parameters of the DLS.

Prototyping of the DLS is now underway. Upstream and downstream prototype modules of the DLS1 are under fabrication. As shown in Fig. 11, each module consists of one coupler cell and ten regular cells. For the coupling tuning, the D's of the regular cells are constant in the upstream and downstream modules, they are the same as the D's of the first and last cells of the DLS1, respectively. The coupling tuning will be performed within this fiscal year.

END TO END SIMULATION

In the original muon linac design, various simulation codes were used. Integration of the simulation using

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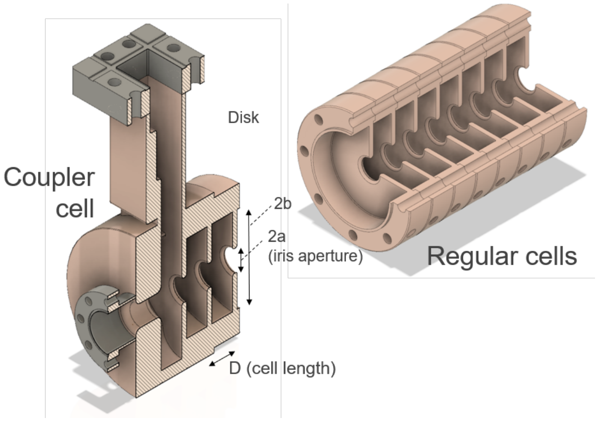

Figure 11: Schematic view of the prototyping parts of the DLS.

GPT [14] is now proceeding. The spin dynamics is also implemented in this simulation. Detail is described in the separated paper [15].

Figure 12 shows the emittance evolution through the muon linac without errors. The horizontal and vertical normalized rms emittances at the exit of the muon linac are 0.28 π mm mrad and 0.22 π mm mrad respectively. An improvement in the horizontal emittance from the original simulation result [16] mainly derived from the optimization of the initial acceleration before the RFQ. The emittance growth is at a tolerable level. The rms momentum spread at the exit of the muon linac is 0.036%.

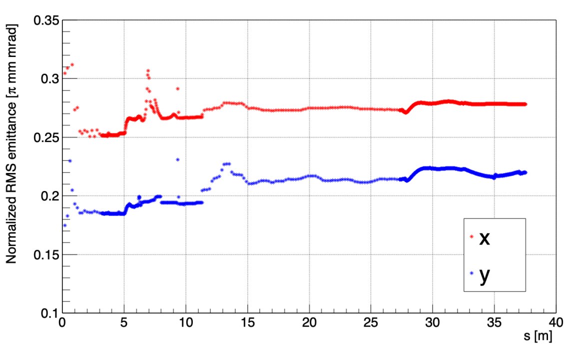

Figure 12: Emittance evolution from the RFQ entrance to the linac exit.

SUMMARY

At J-PARC, the development of he muon linac for the muon g-2/EDM experiment is proceeding. The design work has been almost finished, and the prototyping of each accelerator element is in progress. The re-acceleration scheme has been demonstrated using a test RFQ. Epithermal negative muonium ions were accelerated up to 89 keV. The high-power test of the prototype IH-DTL has been successfully performed, and the fabrication of the IH-DTL production model is completed. The assembly of the first tank of the DAW will be finished within this fiscal year. The prototyping of the DLS coupler cell is also done in this fiscal year. The next milestones are the demonstration of the USM acceleration using RFQ, and the muon acceleration using the IH-DTL. The USM acceleration will be done using a test RFQ again in this year before the completion of H-line. When the H-line will be available, RFQ II and IH-DTL will be installed and the muon acceleration experiment is planned in 2024. After the official approvement of the construction budget of the E34 experiment, a dedicated building for the muon H-line extension will be built. The muon linac will be installed in this building, and four year construction period including commissioning is expected.

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