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RE-ACCELERATION OF ULTRA COLD MUON IN J-PARC MUON FACILITY

Y. Kondo*, K. Hasegawa, T. Morishita, JAEA, Tokai, Naka, Ibaraki, 319-1195, Japan
M. Otani, Y. Fukao, K. Futatsukawa, N. Kawamura, T. Mibe, Y. Miyake, K. Shimomura,
T. Yamazaki, M. Yoshida, KEK, Oho, Tsukuba, Ibaraki, 305-0801, Japan
R. Kitamura, S. Li, University of Tokyo, Hongo, Tokyo, 171-8501, Japan
Y. Nakazawa, H. Iinuma, Ibaraki University, Mito, Ibaraki, 310-8512, Japan
Y. Sue, T. Iijima, Nagoya University, Nagoya, Aichi, 464-8602, Japan
K. Ishida, RIKEN, Wako, Saitama, 351-0198, Japan
N. Hayashizaki, Tokyo Institute of Technology, Tokyo, 152-8550, Japan
Y. Iwashita, Kyoto University, Kyoto, 611-0011, Japan
Y. Iwata, NIRS, Chiba, 263-8555, Japan
N. Saito, J-PARC center, Tokai, Naka, Ibaraki, 319-1195, Japan
S Bae, H. Choi, S. Choi, B Kim, H. S. Ko,
Seoul National University, Seoul, 08826, Republic of Korea
E. Won, Korea University, Seoul, 02841, Republic of Korea
G. P. Razuvaev, BINP, Novosibirsk State University, Novosibirsk 630090,
Pulkovo Observatory, St. Petersburg, 196140, Russia

Abstract

At the J-PARC muon science facility, re-acceleration systems of ultra-slow muons (USMs), which are obtained via the laser resonant ionization of muonium atoms, to an ultra-cold muon beam are being developed. The obtained muon beam has a low emittance and meets the requirements of such as the transmission muon microscope and the muon g-2/EDM experiment. In the latter experiment, USMs will be accelerated to 212 MeV using a muon dedicated linac. The momentum spread of the accelerated muon beam is 0.1%, and the normalized transverse emittance is approximately 1.5π mm mrad. Proof of the slow muon acceleration scheme is an essential step toward realizing the world's first muon linac. In October 2017, we succeeded in accelerating slow negative muoniums generated using a simpler muonium source, even though they are not USMs, to 89 keV. In this paper, the present design of the muon linac and the result of the world first demonstration of the muon acceleration are described.

INTRODUCTION

The muon (μ) is the second generation charged lepton in the Standard Model of elementary particle physics. Due to its unique properties, artificially generated muons from accelerator facilities have been used for studies in a wide variety of fields. The muon has a spin of 1/2 and decays into an electron or positron and a neutrino with a mean lifetime of 2.2 μs. This means that, by measuring the asymmetry of the decay products, the magnetic properties in materials can be measured using the Muon Spin Rotation/Relaxation/Resonance (μSR) method. A muon beam is generated from pion decay in flight or at rest near the surface of a muon production target: the former is called a decay muon beam and the latter a surface muon beam. The emittance of this type of muon beam is very large compared to ordinary electron and proton beams. Moreover, even if a pion decays at rest, the kinetic energy of the secondary muon is 4 MeV; therefore muons with energies of less than a few MeV cannot be obtained directly from pion decay. To study the near-surface and microscopic properties of materials, a low-temperature muon beam is required. To this end, laser resonant ionization of the thermal muonium technique has been developed at KEK [1] and RIKEN-RAL [2]. Figure 1 shows the principle of this method.

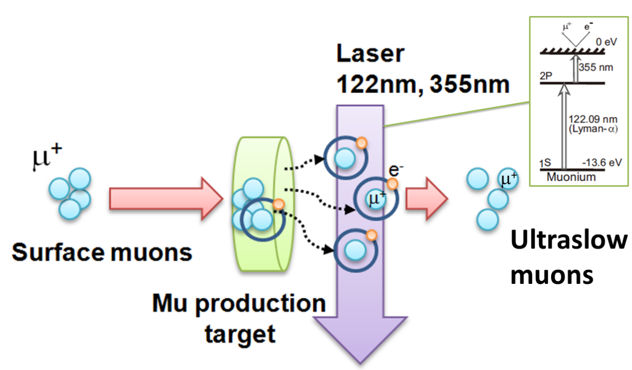

Figure 1: Principle of ultra-slow muon production.

A surface muon (μ^+) is stopped in a hot (2300 K) tungsten target, then the μ^+ captures an electron to become the muonium atom (Mu; μ^+e^-). This Mu is thermally evaporated from the target. Lasers with wavelengths of 122 nm and 355 nm are exposed to resonantly ionize the Mu. Using

* yasuhiro.kondo@j-parc.jp

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this method, μ^+ with a kinetic energy of 0.2 eV, so called ultra-slow muon (USM), can be obtained.

If the USM is re-accelerated, a transmission muon microscope can be realized [3]. Because the mass of the muon is 200 times larger than that of the electron, the transmission depth of a 10-MeV muon is approximately 10 μm. This enables the three-dimensional imaging of living cells, which is impossible with the use of transmission electron microscopes. The re-accelerated USM is referred as an ultra-cold muon beam because the emittance of such a muon beam is extremely small compared to that of a muon beam directly obtained from pion decay.

From a particle physics point of view, muons are suitable to study elementary interactions because muons are an elementary particles similar to electrons. Due of its heavier mass, the muon is more sensitive to unknown particles beyond the Standard Model via the leading order correction. The muon anomalous magnetic moment $a_\mu = (g-2)_\mu/2$ is one of the most promising signals of this type of physics. A new experiment to measure the muon g-2 and electric dipole moment (EDM) using re-accelerated USMs is being planned as J-PARC E34 [4].

Both the development of the transmission muon microscope and the muon g-2/EDM experiment will be performed at the Japan Proton Accelerator Research Complex (J-PARC) muon science facility (MUSE) [5]. In this paper, the re-acceleration activities of ultra-slow muons in MUSE, in particular the muon linac for the muon g-2/EDM experiment are described.

J-PARC MUON SCIENCE FACILITY

The MUSE facility is a part of the J-PARC Materials and Life science experimental Facility (MLF). Figure 2 shows a schematic view of the J-PARC MLF.

Figure 2: Schematic view of the J-PARC MLF.

Negative hydrogens are accelerated with a 400-MeV linac and injected into a 3-GeV Rapid Cycling Synchrotron (RCS) using the charge-exchange injection method. The 3-GeV, 1-MW proton beam extracted from the RCS penetrates a muon production target and reaches a mercury target for neutron production.

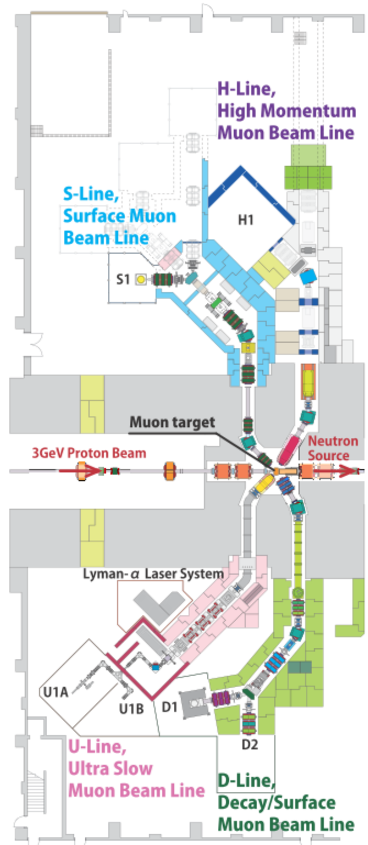

Figure 3: Schematic view of J-PARC MUSE.

Two of the four beamlines of MUSE (Figure 3) are related to USMs. The U-line [6] is dedicated to materials science using USMs. The U1A experimental area is equipped with a μSR spectrometer. The USMs can be electrostatically accelerated up to 30 keV. In the U1B experimental area, developments of the transmission muon microscope, such as a muon acceleration test using an induction cavity [7], will be conducted.

The H-line [8] is for particle physics experiments and the transmission muon microscope. At first, the H1 experimental area will be constructed for particle physics experiments using surface/decay muons. Then, the beamline will be extended outside the current MLF building and the transmission muon microscope and muon linac for the muon g-2/EDM experiment will be installed. A surface μ^+ intensity of $\sim 10^8$ /s is expected on the USM production target [9].

MUON LINAC FOR g-2/EDM EXPERIMENT

Currently, the most precise measurement of the muon anomalous magnetic moment a_μ was achieved by the E821 experiment at Brookhaven National Laboratory [10]. The precision is 0.54 ppm and the measured value is approximately three standard deviations from the Standard Model prediction. The E34 experiment aims to measure a_μ with a precision of 0.1 ppm and the EDM with a precision of

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1×10^{-21} e·cm. E821 directly used a decay muon with a momentum of 3 GeV/c. To the contrary, E34 will use an ultra-cold muon beam to reduce the systematic uncertainties. The required transverse momentum spread $\Delta p_T/p$ is less than 10^{-5}, and the assumed transverse emittance is 1.5 π mm mrad. To satisfy this requirement, the USM will be accelerated to 212 MeV. The muons need to be accelerated in a sufficiently short time compared to the muon lifetime of 2.2 μs to suppress the decay loss. A muon linac enables this quick acceleration. Table 1 summarizes the main parameters 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%

As mentioned in the previous section, the muon is 200 times heavier than the electron, therefore the velocity evolution of the muon is slower than that of the electron, as shown in Figure 4. Therefore, technologies for both proton and electron linacs are used, as shown in Figure 5.

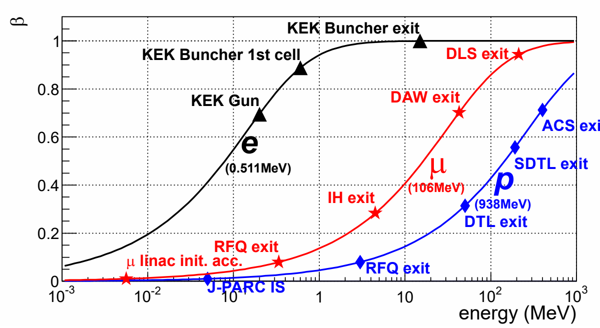

Figure 4: Comparison of the velocity evolution with energy for electron (KEKB injector [11]), proton (J-PARC H⁻ linac [12]) and muon linacs.

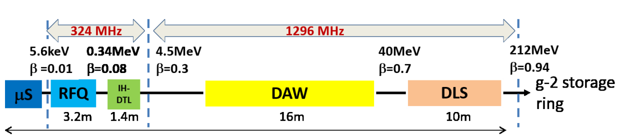

Figure 5: Configuration of the muon linac.

To obtain higher efficiency and reduce the energy of the USM, a silica aerogel target is used for the muonium production target of the USM source for E34 [13]. In this case, the kinetic energy of the USM is 25 meV. The generated USMs are initially accelerated and injected into a radio frequency quadrupole linac (RFQ) using an electrostatic acceleration and focusing system, the Soa lens [9].

To reduce the cost, a spare RFQ of the J-PARC linac [14], shown in Figure 6, will be used. The resonant frequency of this RFQ is 324 MHz, and the muons are accelerated to 0.34 MeV [15].

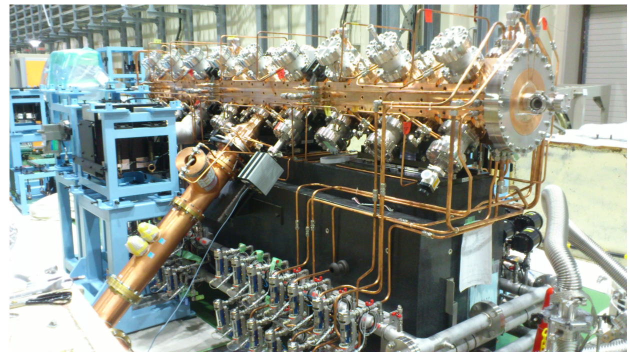

Figure 6: Photo of J-PARC RFQ II.

Due to the profile of the surface muons on the USM production target, the horizontal and vertical normalized rms emittances at the RFQ injection are 0.38 π mm mrad and 0.11 π mm mrad respectively. In the current reference design, this horizontal value limits the horizontal emittance at the exit of the muon linac. Moreover, due to the spatial distribution along the beam axis at the laser point, the pulse length at the RFQ entrance is spread to 10 ns, as shown in Figure 7, despite the laser exposure time being 1 ns. Therefore, the beam pulse is separated into three bunches by the RFQ.

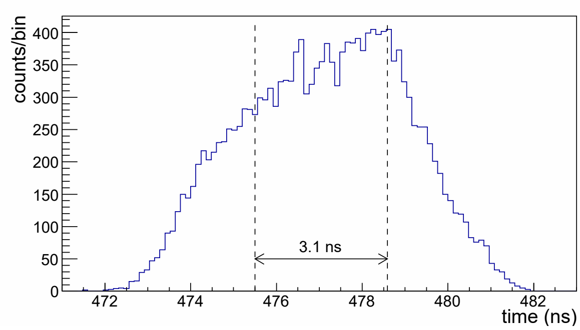

Figure 7: Time structure of the μ^+ beam at the RFQ entrance.

Following the RFQ, an interdigital H-mode drift tube linac (IH DTL) is used to accelerate the muons to 4.5 MeV [16]. One of the major merit of the IH DTL is that the drift tubes can be machined as a monolithic structure. Figure 8 shows the center-plate part of a six-cell prototype IH DTL. The cavity is formed by attaching half cylinder structures to both sides of this center plate. This prototype IH DTL can accelerate muons to 1.3 MeV. The final-version IH DTL can be fabricated using the same method.

Then, muons are accelerated to 40 MeV through a disk and washer (DAW) coupled cavity linac section [17]. The

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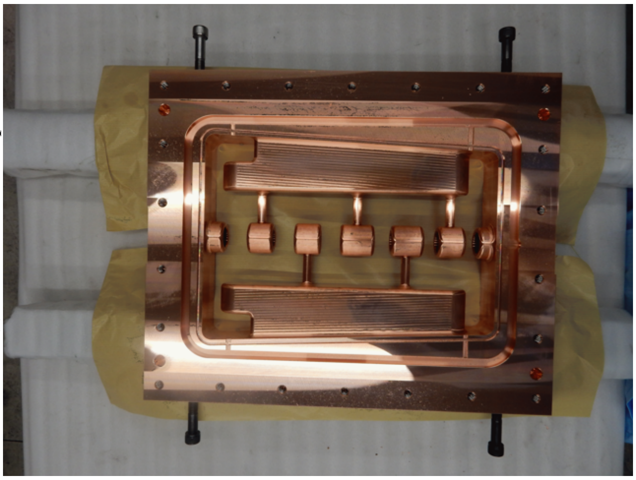

Figure 8: Center plate of 6-cell prototype IH DTL.

acceleration frequency is increased to 1296 MHz and the accelerating gradient E_0 is 5.6 MV/m.

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 disk-loaded 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 [18]. The expected E_0 is 20 MV/m.

Figure 9 shows the emittance evolution through the muon linac, and the results of the particle simulation are summarized in Table 2. The horizontal and vertical normalized rms emittances at the exit of the muon linac are 0.33 π mm mrad and 0.21 π mm mrad respectively. As mentioned above, the horizontal emittance is limited by the surface muon profile on the Mu production target. The most significant cause of vertical emittance growth is the mismatch to the RFQ acceptance. After the RFQ, the growth ratio is at a tolerable level. The muon decay loss occurs primarily in the low energy section because the Lorentz γ is small. The rms momentum spread at the exit of the muon linac is 0.04%.

Table 2: Summary of the Particle Simulation Through the Muon Linac The ε_x and ε_y denote the horizontal and vertical normalized rms emittances, respectively.

	Init.	RFQ	IH	DAW	DLS
Frequency[MHz]	-	324		1296	
Energy[MeV]	0.056	0.34	4.5	40	212
β	0.01	0.08	0.28	0.69	0.94
ε_x[π mm mrad]	0.38	0.30	0.32	0.32	0.33
ε_y[π mm mrad]	0.11	0.17	0.20	0.21	0.21
Transmission[%]	87	95	100	100	100
Decay loss[%]	17	19	1	4	1

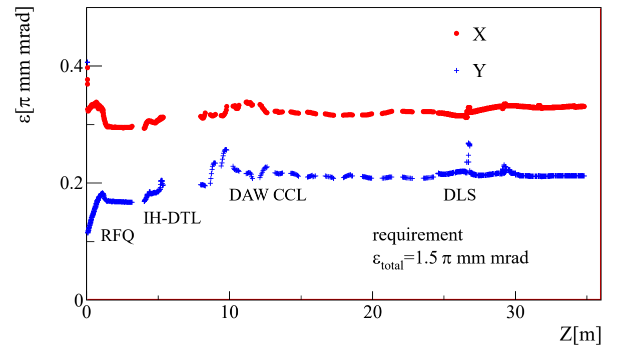

Figure 9: Emittance evolution from the RFQ entrance to the linac exit.

DEMONSTRATION OF MUON ACCELERATION

Even though muon acceleration is essential to the applications described in the introduction, it is still unproven except for simple electrostatic acceleration. Therefore, muon acceleration needs to be demonstrated as soon as possible prior to the construction of the actual linac. However, the first problem was where to conduct the experiment. The H-line is not yet available; however, the available experimental areas are too small to install RFQ II. Here, we focused on a prototype high-current RFQ for the J-PARC linac [19]. The length of this RFQ corresponds to two thirds that of RFQ II; therefore, it can be installed in the D2 area, which is a multi-purpose experimental area of MUSE [20], as shown in Figure 10. This RFQ can accelerate muons from 5.6 keV to 89 keV.

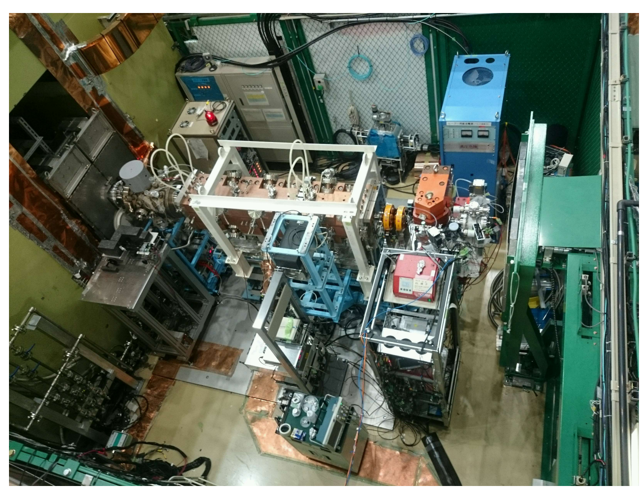

Figure 10: J-PARC prototype RFQ managed to be installed in the D2 area.

The second problem was the slow muon source. The laser ionization USM source is a large scale and complicated apparatus; therefore, an earlier and simpler slow muon source is necessary to conduct the muon acceleration experiment. A muon-cooling scheme using a simple metal degrader is

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suitable for this purpose. We used epithermal negative muoniums (Mu$^-$; $\mu^+e^-e^-$) generated from μ^+'s degraded via the electron capture process [21].

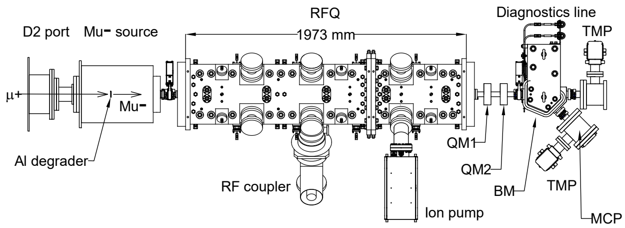

Figure 11: Schematic drawing of the setup of the muon acceleration experiment.

Figure 11 shows a schematic drawing of the experimental setup [22]. The MUSE facility provides a 2.9-MeV 25-Hz surface muon (μ^+) beam. For this experiment, the beam power of the RCS was 300 kW. With this beamline setting, the μ^+ intensity was estimated to be 3×10^6 /s. The μ^+'s were incident on an aluminum degrader with dimensions of 43×40 mm^2 and a thickness of 200 μm. The μ^+'s were decelerated through the Al degrader, and some μ^+'s captured two electrons to become Mu$^-$'s at the downstream surface of the Al degrader. Using an Soa lens, the generated Mu$^-$'s were accelerated to 5.6 keV and focused on the entrance of the RFQ. Figure 12 shows an interior view of the Mu$^-$ source.

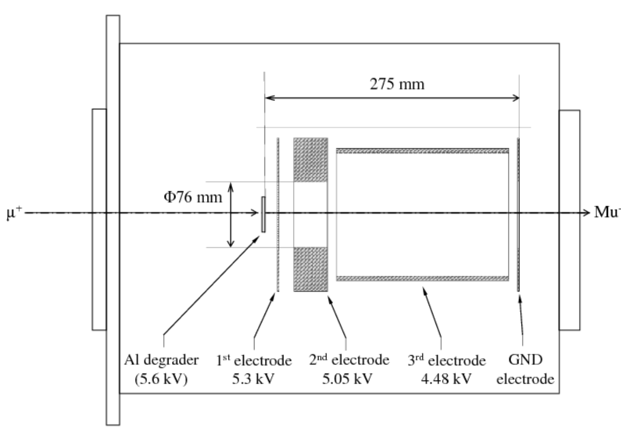

Figure 12: Interior view of the Mu$^-$ source.

To use the H$^-$ RFQ for muon acceleration, the inter-vane voltage needs to be normalized to the muon mass and the input velocity needs to be the same as that of the H$^-$. The extracted beam properties were measured using a beam diagnostics line. The beam was transferred using two quadrupole magnets (QM1 and QM2). The charge and momentum of the particle can be selected with a bending magnet (BM). The bending angle of an 89-keV muon is 45° with a BM current of 11.1 A. A microchannel plate (MCP, Hamamatsu photonics F9892-21 [23]) was located at the downstream end of the 45° line. Using the MCP signal, the time of flight (TOF) of the Mu$^-$ was measured. Figure 13 shows the TOF spectra with and without the RF operation after a pulse-height cut with a threshold of 100 mV was applied. With the RF operation, a clear peak was observed at 830 ns. This is consistent with the estimated TOF of the accelerated Mu$^-$ obtained by the simulation. The hatched histogram in Fig. 13 represents the simulated TOF spectrum of the accelerated Mu$^-$. Therefore, the observed TOF peak is due to the Mu$^-$'s accelerated by the RFQ to 89 keV.

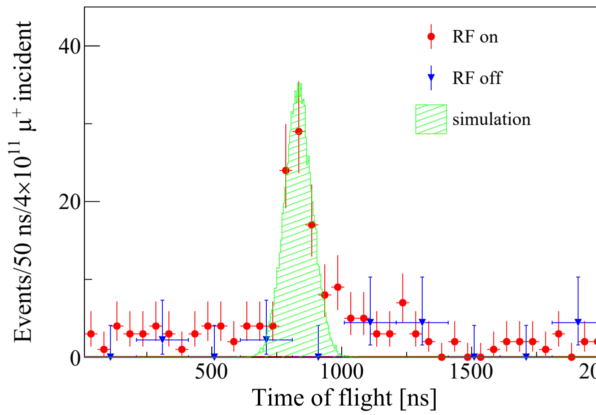

Figure 13: TOF spectra with RF on and off. The clear peak of the RF on spectrum at 830 ns corresponds to the accelerated Mu$^-$'s. A simulated TOF spectrum of the accelerated Mu$^-$'s is also plotted.

SUMMARY

Re-acceleration of ultra-slow muons (USMs) can be applied in various research field. In the J-PARC muon science facility, efforts to accelerate USMs are underway: one of them is the muon linac for the muon g-2/EDM experiment. The reference design of the muon linac has been established, and the prototyping of each accelerating cavity is in progress. In the development of the muon linac, the world's first muon acceleration using an RF accelerator was demonstrated. Slow negative muonium ions ($\mu^+e^-e^-$) were accelerated to 89 keV with an RFQ. The next step is the demonstration of muon acceleration using the IH DTL. We have already fabricated a 6-cell prototype of the IH DTL. When the H-line will be available, RFQ II and this IH DTL will be installed and the muon acceleration experiment will be conducted.

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