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Interdigital *H*-Mode Drift Tube Linear Accelerator for a Muon Linear Accelerator †

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Abstract: The muon anomalous magnetic moment ($g-2$) measurement at the Fermilab National Accelerator Laboratory (FNAL-E989) is consistent with a previous experiment at the Brookhaven National Laboratory (BNL-E821), and these results show a deviation of 4.2 standard deviations from the prediction of the Standard Model. This deviation may suggest the existence of unknown particles, and a completely different approach from previous experiments is needed for further verification. The J-PARC experiment's objective is to measure the muon g-2 and the electric dipole moment (EDM) with high precision using a new method with a low-emittance muon beam generated by RF linear acceleration. In this paper, the development of an interdigital *H*-mode drift tube linac (IH-DTL) for the muon linear accelerator is described.

Keywords: muon; dipole moment; linear accelerator

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1. Introduction

The muon anomalous magnetic moment ($g-2$) and the muon electric dipole moment (EDM) are promising quantities that are highly sensitive to new physics and serve as a guideline for validating the standard model (SM). Detecting the finite value of the muon EDM represents a violation of charge conjugation and parity reversal (CP) and implies the existence of physical phenomena beyond the SM. Furthermore, the measurement of the muon $g-2$ has a long history as an attempt to validate the theoretical calculation of the SM. The current global average of the muon $g-2$ [1,2] shows a discrepancy of 4.2 standard deviations from what was predicted by the SM [3]. This discrepancy is expected to have the potential to indicate the existence of unknown particles, and it is highly significant to verify this using a different measurement method than the conventional one.

At the Japan Proton Accelerator Research Complex (J-PARC), the muon $g-2$/EDM experiment (J-PARC E34 [4]) strives to measure the muon $g-2$ with the precision of 0.45 parts per million (ppm) and to search for the muon EDM at 10^{-21} $e \cdot$cm sensitivity. One of the key technologies employed in the E34 experiment involves utilizing a low-emittance muon beam. This approach differs from prior experiments that used muon beams with a large emittance derived from pion decay. It reduces beam-derived systematic uncertainties.

In the E34 experiment, the required transverse emittance is 1.5 π mm mrad, and the momentum spread is less than 10^{-3}. Ultra-slow muons (USMs) are produced by the laser dissociation of thermal muonium formed by a silica aerogel target to realize this low-emittance muon beam. USMs have a kinetic energy of 25 meV and then are accelerated to relativistic energy of 212 MeV using a radio frequency (RF) linear accelerator (linac). The muon's lifetime is finite at 2.2 µs; thus, muons must be accelerated using a linac to avoid decay losses for the E34 experiment. Table 1 shows the main parameters of the muon linac.

Table 1. Main parameters of the muon linac.

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

2. Muon Linear Accelerator

Figure 1 shows a schematic view of the muon linac.

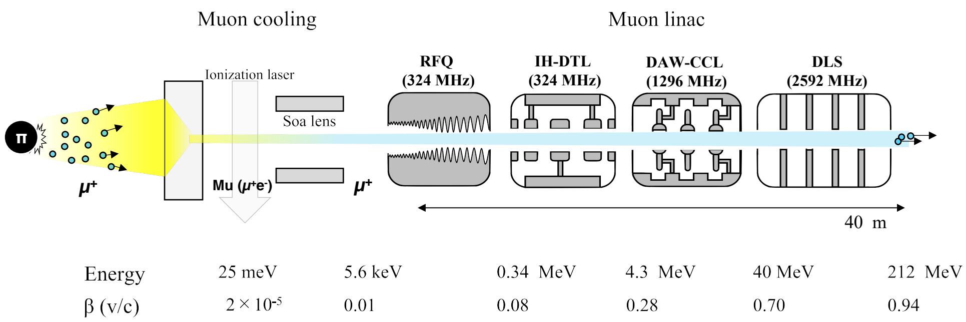

Figure 1. Overview of the muon linac.

To begin with, the USMs are electrostatically accelerated by a Soa lens [5]. The muons are then bunched and accelerated up to β = 0.08 using a radio frequency quadrupole (RFQ) linac [6] with an operating frequency of 324 MHz. In the low *beta* region, an interdigital *H*-mode drift tube linac (IH-DTL) [7] accelerates bunched muons up to β = 0.08 to 0.28. This IH-DTL operates at a resonant frequency of 324 MHz. Afterward, a disk and washer coupled cavity linac (DAW-CCL) [8] with an operating frequency of 1296 MHz is utilized as the middle β region with β = 0.28 to 0.70. For the high β region of β = 0.70 to 0.94, disk-loaded structure (DLS) [9] traveling wave linac is employed. The DLS operates at a resonant frequency of 2592 MHz to achieve a high accelerating gradient.

The basic linac design and numerical beam dynamics calculations have already been completed [10]. In 2017, we demonstrated the first muon acceleration up to 89 keV using a spare RFQ [11]; we have achieved the first milestone in muon linac development. As the following milestone, the development of the IH-DTL, DAW, and DLS is promoted. In this paper, the development status of the IH-DTL is presented.

3. Development of the IH-DTL

In designing the IH-DTL, the alternating phase focusing (APF) [12] method was chosen as the transverse focusing technique to obtain high acceleration efficiency while keeping fabrication costs low. In the APF method, the beam can be transversely focused by adjusting the synchronous phase of each cell according to arbitrary preferences. This approach eliminates the need for a focusing element like an electromagnet, significantly simplifying the structure of the drift tube and other components. The APF method has been successfully implemented in hadron therapy accelerators proving its effectiveness as a technology [13–15]. Figure 2 shows the optimized synchronous phase array for the APF method.

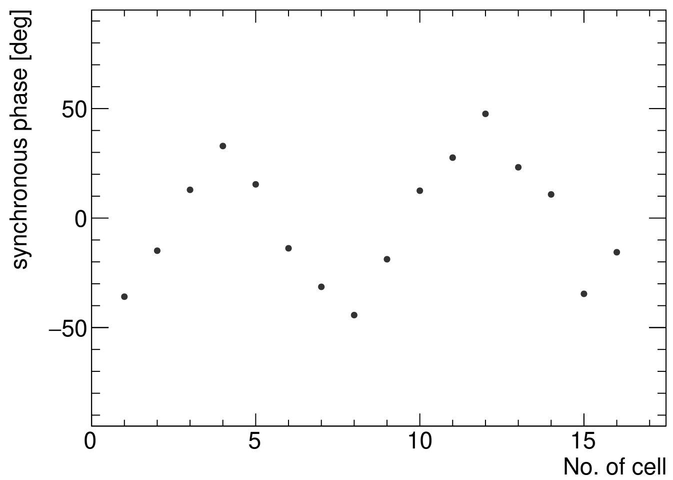

Figure 2. Synchronous phase array of the APF method.

The IH-DTL possesses a simple structure, which is another benefit it offers. There are two options available for H-mode DTLs. The first is the IH type, which operates in TE_{11} mode, while the second is the crossbar H-mode (CH) in the TE_{21} mode. The CH-DTL, characterized by a vertical and horizontal stem crossing, has a more intricate structure, making it more costly to produce. On the other hand, the IH-DTL aligns only the upper and lower stems, allowing for a more straightforward cavity structure with just a center plate and two semi-cylindrical side shells. This simplified structure facilitates cavity assembly and ensures the proper alignment of drift tubes. Additionally, it offers cost-effectiveness. Based on these advantages, we have adopted the IH-DTL using the APF method.

Table 2 summarizes the design parameters of the APF IH-DTL, calculated by CST MICROWAVE STUDIO (MWS) [16]. The maximum surface field is designed as twice the Kilpatrick limit (E_k) [17]. We have already successfully demonstrated high-power testing with a short-length IH-DTL as a prototype [18].

Table 2. Design parameters of the IH-DTL.

Parameter	Value
The number of cells	16
Cavity length (m)	1.45
Unloaded quality factor	10,910
Averaged accelerating field (MV/m)	3.6
Maximum surface field (MV/m)	35.4 (2.0 E_k)
Nominal power (kW)	310

Figure 3 shows the mechanical structure of the APF IH-DTL for the E34 experiment. The cavity is made of oxygen-free copper (OFC) and is formed by bolting a center plate with monolithic DTs [19] and semi-cylindrical side shells. The resonant frequency of the bare cavity was designed as 321.38 MHz for tunability and can be set to the operating frequency by adequately adjusting the six slug tuners.

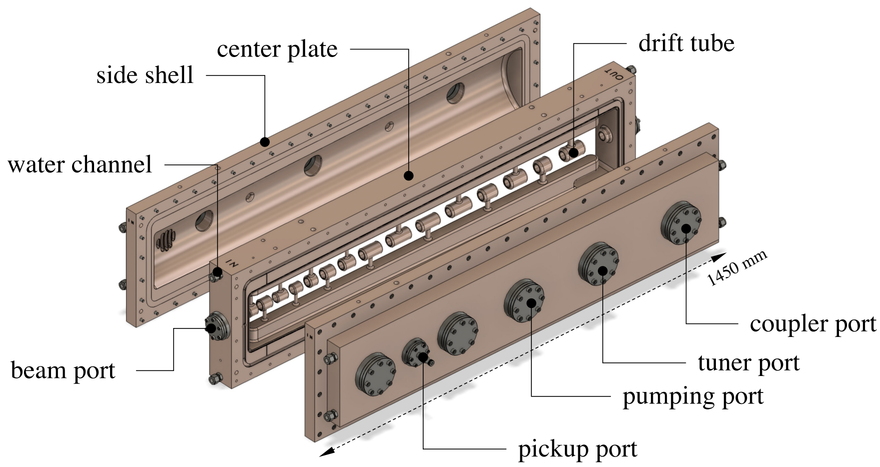

Figure 3. The mechanical structure of the APF IH-DTL. The drift tubes are monolithically machined on the center plate.

Then, the IH-DTL was fabricated. Figure 4 shows a photograph of the fabricated center plate. The center plate is machined from the OFC plate by the gun drill process. The machining accuracy of the drift tube radius was less than 50 µm, which comfortably satisfied the requirements calculated through a field error study using CST MWS.

Figure 4. The fabricated center plate of the IH-DTL.

After the fabrication of the IH-DTL, a low-power test was conducted. The measured frequency and unloaded quality factor (Q_0) were 322.36 MHz and 10,080, respectively. The measured Q_0 corresponds to 92.4% of the simulated Q_0. It was confirmed that the measured frequency and Q_0 were consistent with those observed in the simulation results.

Then, the field distribution was measured by the bead pull method [20]. An aluminum spherical bead with a radius of 1.5 mm was pulled along the beam axis at a constant speed, and the frequency shift was measured using a vector network analyzer. Figure 5 shows the result of the bead pull measurement. The top figure represents the frequency shift ($\Delta f/f$) along the beam axis. The blue marker shows the measured frequency shift, and the solid line shows the simulated frequency shifts were calculated from $\Delta f/f \propto \varepsilon_0 E^2 - \mu_0 H^2/2$. Where ε_0 is the dielectric constant of the vacuum, and μ_0 is the magnetic permeability of the vacuum. The bottom figure shows the field error, which is the difference between the square root of the measured and simulated frequency shifts. The black marker shows the averaged field error values within the gap areas, and the horizontal bar represents the gap areas. The averaged field error values are all less than 2%, which revealed that the field distribution reproduced the simulation results well.

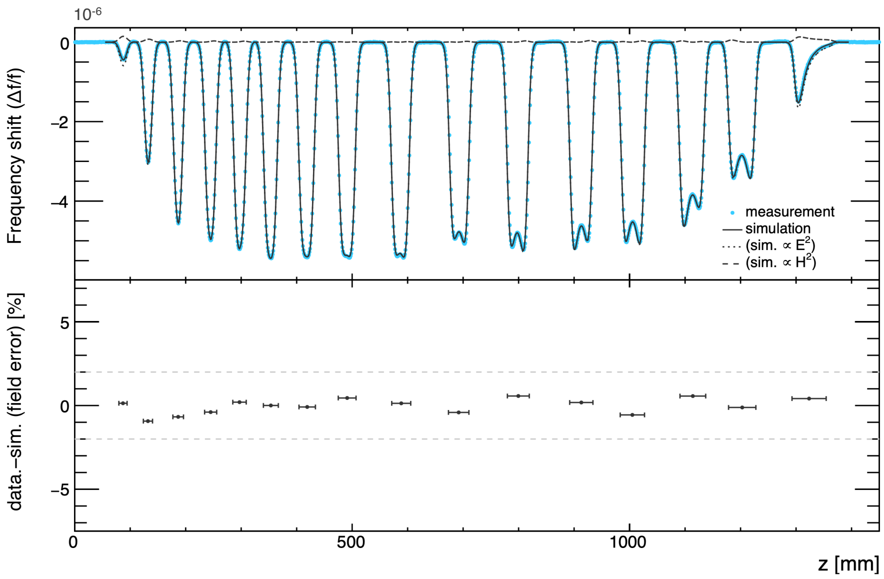

Figure 5. Top: the frequency shift along the beam axis by the bead pull method. Bottom: the field error in the on-axis field distribution of the gap area.

4. Summary and Prospects

The development of a muon linac for the J-PARC muon $g-2/\text{EDM}$ experiment is underway. The basic design has almost been completed, and the prototyping of each accelerator element is proceeding. Recently, the high-power test of the prototype IH-DTL was successful. Moreover, based on this prototype development, the fabrication of the IH-DTL was completed. The demonstration test of muon multi-stage acceleration using RFQ and the IH-DTL is planned for 2024. Furthermore, after the construction budget for the E34 experiment is approved, the installation and commissioning of the muon linac, including DAW and DLS, are scheduled.

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