DTL DESIGN FOR MUON LINAC

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Abstract

We have developed a drift-tube linac (DTL) design for a muon linac, in order to measure the anomalous magnetic moment and electric dipole moment (EDM) of muons at J-PARC. The DTL accelerates muons from $\beta = v/c = 0.08$ to 0.27 at an operational frequency of 324 MHz. The output beam emittances are calculated as 0.30π and 0.17π mm mrad in the horizontal and vertical directions, respectively, which satisfies the experimental requirement. The design, results, and comparisons to other acceleration structures are described in this paper.

INTRODUCTION

The use of a low emittance muon beam has been discussed in several scientific fields [1–3]. One of those is the quest for hunting beyond the Standard Model (SM) of elementary particle physics. In the muon anomalous magnetic moment $(g-2)_\mu$, the SM prediction and the measured value with a precision of 0.54 ppm [4] differs by about three standard deviations. Since this is considered to be due to unknown interactions or particles beyond the SM, further investigations are desirable. The low emittance muon beam will provide more precise measurements since the dominant systematic uncertainties in the previous experiment [4] resulted from the muon beam dynamics in the muon storage ring.

We are developing a muon linac for the $(g-2)_\mu$ experiment [5] at the Japan Proton Accelerator Research Complex (J-PARC) to produce the low emittance muon beam. 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 [6]. Following the RFQ, a drift tube linac (DTL) is used to accelerate muons in the low-β section.

Table 1 shows the main parameters of the low-β section. We are developing three types of DTLs as an acceleration structure in low-β section: inter-digital H-mode (IH) DTL, crossbar H-mode (CH) DTL, and conventional Alvarez DTL. The IH and CH designs can be found elsewhere [7, 8]. This paper represents designs for the Alvarez DTL and comparisons to other structures.

MUON DTL DESIGN

Procedures for the DTL design are as follows: cell design, dynamics design, cavity design and PIC simulation. Details of each step are explained in this section.

Table 1: Main Parameters of the Low-β Section

Input energy	0.34 MeV
Output energy	~ 4 MeV
Beam intensity	1×10^6 /s
Beam pulse width	10 nsec
Number of bunches	3 /pulse
Repetition rate	25 Hz
Normalized transverse emittance	0.3π mm mrad

Cell design

The DTL cells for several velocity values are designed with SUPERFISH [9]. Figure 2 shows typical electric field pattern of the DTL cell. The bore radius is 1 cm and the inner radius of the cavity is 26.45 cm. Table 2 summarizes basic parameters of the designed cell for β = 0.08–0.26. The gaps per unit cell length $(g/\beta\lambda)$ become larger in order to maintain a constant frequency. The transit-time factor and the shunt impedance do not decrease strongly in this velocity region.

Table 2: Cell Parameters for Different β

β	T	T'	S	S'	$g/\beta\lambda$	Z	E_{max}/E_0
0.080	0.759	0.066	0.488	0.049	0.150	54.3	7.5
0.100	0.813	0.053	0.446	0.052	0.165	58.4	7.0
0.125	0.847	0.045	0.416	0.052	0.183	62.0	6.5
0.150	0.862	0.041	0.404	0.053	0.202	64.1	6.1
0.175	0.866	0.040	0.404	0.053	0.221	65.4	5.9
0.200	0.863	0.041	0.413	0.055	0.241	66.2	5.8
0.230	0.853	0.044	0.431	0.057	0.265	66.5	5.7
0.260	0.838	0.049	0.454	0.059	0.288	66.4	5.6

Dynamics design

Longitudinal dynamics design is conducted by PARMILA [10]. A synchronous phase ϕ_0 is fixed to be −30 degrees along all cells. An average axial electric-field (E_0) is set to be 4.5 MV/m. Based on peak to average ratio (E_{max}/E_0) estimated by SUPERFISH, the maximum field is expected to be 1.8 times Kilpatrick limit [11, 12]. Based on those parameters, acceleration with seven cells achieves the kinetic energy of 4.2 MeV.

Transverse dynamics are designed by PARMILA and TRACE3D [13]. Transverse focusing is implemented by a magnetic quadrupole inside the drift tube with FODO lattice. In this configuration, matching parameters for the DTL is derived by TRACE3D. To realize these matching parameters, a matching section between the RFQ and the DTL is designed with four quadrupole magnets and two bunch-

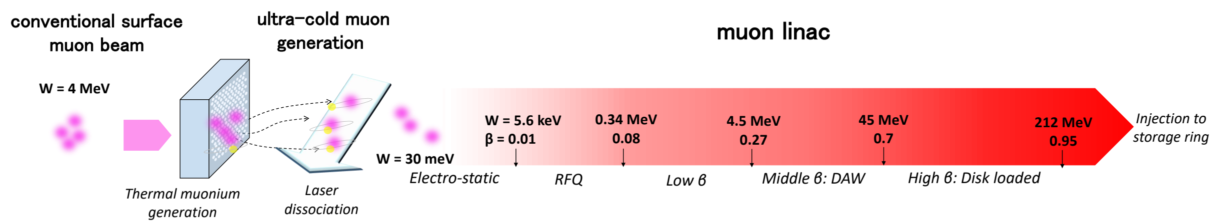

Figure 1: Configuration of low-emittance muon beam.

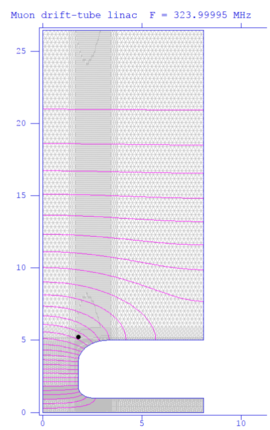

Figure 2: Electric field calculated by SUPERFISH.

ers. Figure 3 shows entire design of the matching and DTL sections.

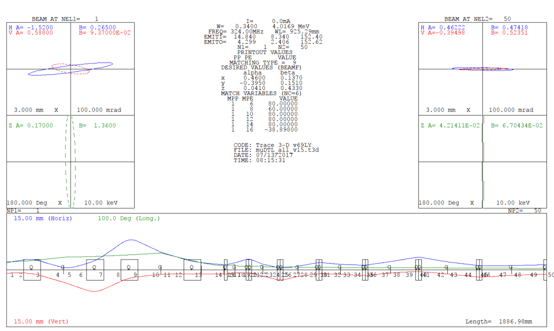

Figure 3: Matching design of the DTL using TRACE3D.

Cavity design

The entire DTL cavity is constructed using the CST Micro Wave (MW) Studio [14]. The three-dimensional solver is used to calculate the electro-magnetic field and estimate required power. Figure 4 shows the three-dimensional model of the cavity in CST MW Studio. The structure consists of a cylindrical cavity and six drift tubes mounted on the top side of the cavity.

The resonant frequency is calculated to be 324.3 MHz, which is consistent with the SURPERFISH result. Figure 5 shows on-axis electric-field profile of the working mode.

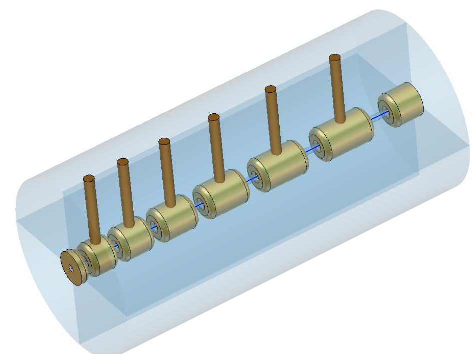

Figure 4: Three-dimensional model of DTL cavity in CST MW Studio calculation.

It is relatively flat through the cavity. The calculated electromagnetic parameters are summarized in Table 3. All field-dependent quantities are scaled to have the average on-axis field E_0 = 4.5 MV/m and power-related values are given at 100% duty (actual duty is ~ 0.1%) for conductivity $\sigma = 5.8 \times 10^7$ S/m.

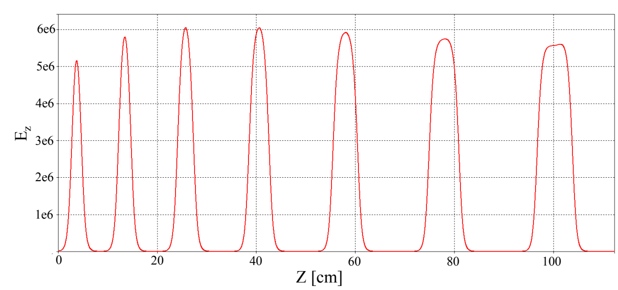

Figure 5: Longitudinal electric-field profile along the cavity.

Table 3: Electromagnetic Parameters of the Muon DTL Cavity

Parameter	Value
Quality factor (Q_0)	44800
Effective shunt impedance	39 MΩ/m
Maximum electric field	$1.64E_k$
Surface rf power loss	392 kW
Maximal surface loss density	196 W/cm^2

PIC simulation

Finally the beam particle trajectory is simulated using the General Particle Tracer (GPT) [15]. The electromagnetic fields calculated in CST MW Studio and quadrupole field in the DTL are implemented in the code and the particle dynamics are calculated numerically. Particle distribution obtained by the simulation of upstream structures [16, 17] is used for this study.

Figure 6 shows the phase-space distribution at the exit of the DTL. Emittance growth is less than few percent. Transmission through the DTL section is almost 99.9% and the loss due to the muon decay is estimated to be 1.0%.

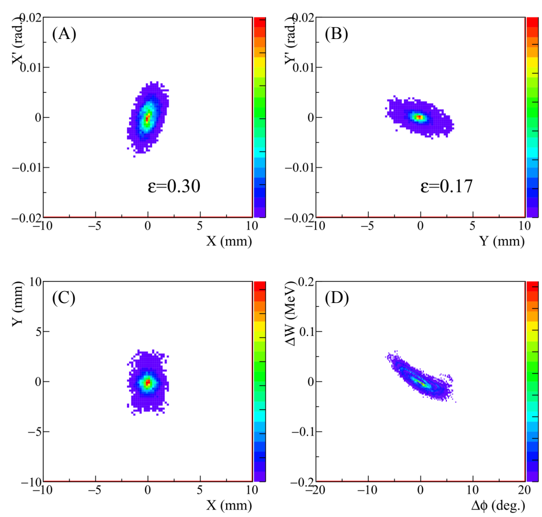

Figure 6: Simulated particle distribution at the DTL exit. (A) the horizontal divergence angle x' vs x, (B) the vertical divergence angle y' vs y, (C) y vs x, and (D) $\Delta W (W-4.2$ MeV) vs $\Delta\phi$.

COMPARISON TO OTHER STRUCTURES

Table 4 summarizes basic parameters of design for several DTL structures: DTL, IH [7], and CH [8]. The output energy and required RF power are almost comparable among all the structures. The emittance growth is comparably small and the output emittances satisfy the experimental requirement in all the structures. Output emittances in the DTL structure are smaller compared to those in the IH and CH structures. It is because the IH and CH employ an alternating phase focusing (APF) scheme for transverse focusing. In addition, the emittance in the y-direction is the IH structure is slightly larger compared to others because there is a vertical dipole field component.

Table 4: Design Parameters for DTL, IH, and CH

	DTL	IH	CH
Input energy [MeV]	0.34	←	←
Output energy [MeV]	4.2	4.3	4.1
RF power loss	392	330	360
ε_x [norm., rms, π mm mrad]	0.30	0.316	0.317
ε_y [norm., rms, π mm mrad]	0.17	0.195	0.188
ε_z [π MeV deg]	0.0204	0.0303	0.0315

SUMMARY

In this paper, designs of the muon DTL for the J-PARC $g-2$/EDM experiment were presented. The beam emittance after the muon DTL was calculated to be 0.30π and 0.17π mm mrad in the x- and y-directions, respectively. It satisfies the experimental requirement.

ACKNOWLEDGMENT

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