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Comprehensive studies of linear accelerators for muons in the medium velocity range

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Abstract. The muon linac has been developed at J-PARC to accelerate muons from thermal energy (25 meV) to 212 MeV using electrostatic extraction and four different types of radio-frequency cavities: RFQ, IH-DTL, DAW-CCL, and disk-loaded structures. Although some of the technologies employed were relatively novel, most proof-of-principle demonstrations have been successfully completed through prototype testing and actual production. Based on these experiences, it has become possible to propose a shorter or more efficient schematic design derived from the current design. In this poster, the new schematic design will be presented.

1 Introduction

High-energy muons with low-emittance beams are in great demand for experiments in particle physics [1, 2], transmission microscopy in materials and life sciences [3], and applications such as muon-based transparent imaging [4]. The advancement and maturation of muon cooling technologies – methods for compressing tertiary beam muons into a small phase-space region – have facilitated significant progress [5, 6, 7, 8] in muon acceleration research, as exemplified by the development of a muon linac at J-PARC [9].

A schematic of the baseline design configuration for the muon linac at J-PARC is shown in Fig. 1. It consists of an Radio-frequency Quadrupole linac (RFQ), an Inter-digital H-mode Drift Tube Linac (IH-DTL), a Disk-And-Washer Couple Cavity Linac (DAW-CCL), and a disk-loaded structure. Thermal muons are generated via laser ionization of thermal muonium [8], and are then extracted and accelerated to 5.6 keV using an electrostatic lens[10]. The RFQ accelerates the muons to 0.34 MeV [11], followed by acceleration to 4.26 MeV by the IH-DTL [12], both operating at 324 MHz. The DAW-CCL further accelerates the muons to 40 MeV at 1296 MHz [13], and the disk-loaded structure accelerates them to 212 MeV at 2592 MHz [14].

The technical design and proof of principle for this new type of linac have been developed and demonstrated. Muon acceleration was first realized through the production of negative muonium and a prototype RFQ [15], and more recently, acceleration of thermal muons was successfully demonstrated [16]. The IH-DTL has already been fabricated and is ready for acceleration [17, 18], which is scheduled for 2027. Prototypes of the DAW-CCL and disk-loaded structures with irregular cell spacing – specifically designed for muons – have been fabricated and tested [19, 20], demonstrating the feasibility of cavity fabrication. These intensive efforts confirm the feasibility of the baseline design and enable the construction of a real machine up to the IH-DTL stage, while also opening the door to more efficient configurations that could enhance the practicality of future stages. One potential improvement is to reconsider the configuration in the medium-velocity range currently covered by the DAW-CCL, as this section is relatively long despite the modest energy gain. Another is to reevaluate the cavity type used in the DAW-CCL: it currently

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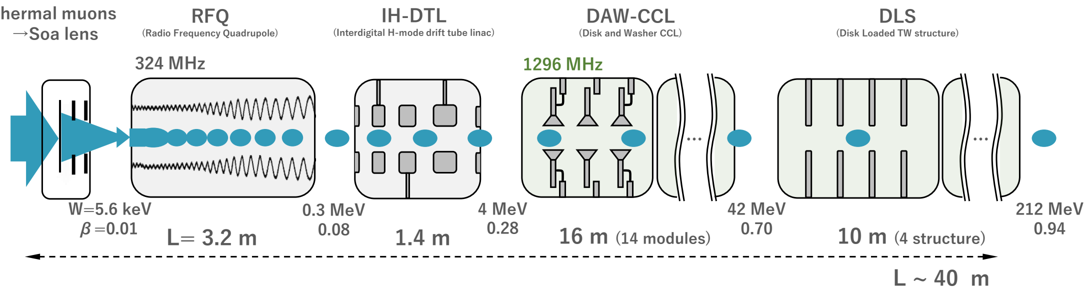


Figure 1: Schematic configuration of the muon linac.

requires 14 different cell types to cover a wide velocity range, which increases cost due to the complexity and variety of components.

In this paper, we present a comprehensive study of the medium-velocity region in the muon linac. First, the design of an Alternating Periodic Structure (APS) is investigated as a potential alternative to the DAW-CCL. Next, a revised configuration for the medium-velocity section is proposed and evaluated. Finally, we summarize the key findings and discuss future directions.

2 APS as an alternative to DAW-CCL

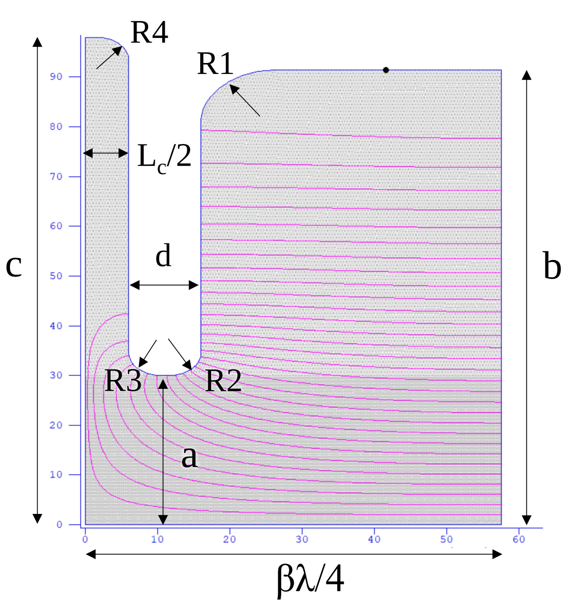
The APS is a well-known accelerating structure proposed in the mid-1960s [21, 22]. Compared to off-axis coupled cavities such as the DAW-CCL, the APS employs on-axis coupling and has a structurally simpler design. Although the effective shunt impedance of the APS is generally lower than that of the DAW-CCL, it serves as a valuable benchmark for comparison when considering overall factors including cost, enabling a comprehensive assessment of each structure. While the performance of APS has been well established and understood for particles traveling at nearly the speed of light [23, 24], its applicability to low-velocity particles has not been thoroughly investigated. Therefore, evaluating its feasibility in the low-velocity region requires a dedicated assessment of its performance in that regime.

The design of APS operating at 1296 MHz for medium-velocity particles was conducted using SUPERFISH[25]. Figure 2 shows the dimensional parameters and their definitions used in the design. The iris radius (a) was determined to ensure sufficiently strong coupling over a 2-meter-long acceleration tank. Chamfer dimensions R_1, R_2, and R_3 were fixed at 8 mm, 4.5 mm, and 4.5 mm, respectively, while R_4 was varied to accommodate the desired coupling cell length (L_c). The disk thickness d was fixed at 10 mm, and the coupling cell length L_c was initially set to 10 mm, as is typical for high-velocity designs, and then gradually reduced; the minimum was set to 4 mm, considering constraints such as manufacturability and thermal management. The inner diameters of the accelerating and coupling cells, b and c, were adjusted to satisfy the confluence condition within a few kilohertz. After verifying the single-cell design satisfied the confluence condition, a 10-cell model was constructed based on the same parameters, and the shunt impedance and other RF properties were evaluated.

Figure 3 shows the electric field calculated by SUPERFISH for the $\beta = 0.4$ design. The effective shunt impedance (ZTT) is evaluated to be 1.1 MΩ/m, which is significantly lower than that of the DAW-CCL, evaluated at 34 MΩ/m. The obtained ZTT is in good agreement with a simplified estimation based on the analytical electromagnetic field of a pillbox cavity, and it is unlikely to be substantially improved even if the coupling cell length is reduced from 4 mm. Although the ZTT increases at higher particle velocities, it still does not reach the performance level of the DAW-CCL. These results suggest that the potential cost savings from simplified cavity fabrication using APS do not sufficiently offset the reduced acceleration efficiency.

3 New Configuration

Although an IH-DTL with an operational frequency exceeding approximately 324 MHz had not been realized during the early development of the muon linac, an IH-DTL operating at 324 MHz for muons has now been successfully demonstrated. Furthermore, performance and operation of IH-DTLs at comparable or higher frequencies have recently been validated in compact proton therapy systems [26, 27]. These results indicate that the upstream portion of the DAW-CCL could be shortened by incorporating



β	0.4-1.0
λ [mm]	231
a [mm]	30
R1 [mm]	8
R2 [mm]	4.5
R3 [mm]	4.5
R4 [mm]	0.4 – 4.5
d [mm]	10
L_c [mm]	4 – 10
b [mm]	93.5 (L_c =1, β=0.4)
c [mm]	103.05 (L_c =1, β=0.4)

Figure 2: Dimensional parameters used in the APS cavity design.

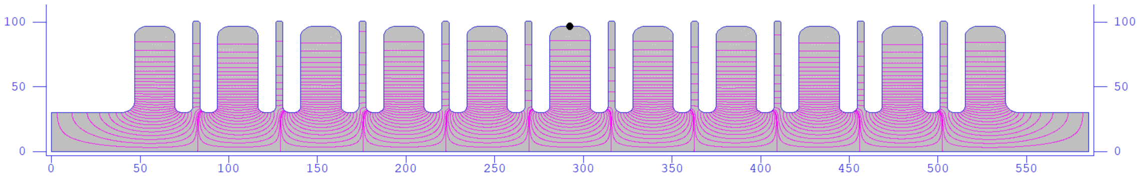


Figure 3: Electric field of the APS cavity optimized for $\beta = 0.4$, obtained through electromagnetic simulation using SUPERFISH.

additional IH-DTL modules operating at the same frequency, providing a more practical and cost-effective configuration.

Figure 4 shows the design of an IH-DTL for muons from 4.26 MeV ($\beta = 0.28$) to 7.25 MeV ($\beta = 0.35$). Total number of cells is 10, and inner cavity length is 1.4 m, and other cavity parameters are summarized in Table 1. Electromagnetic field simulations performed using CST MICROWAVE STUDIO [28] indicate an effective shunt impedance ($\mathrm{ZTTcos}^2(\phi_s)$, where $\phi_s = -20^\circ$) of 30 MΩ/m. This value is higher than or comparable to that of the DAW-CCL, which is 18 MΩ/m at $\beta = 0.3$ and 34 MΩ/m at $\beta = 0.4$ [13], thus demonstrating the feasibility of the design. Assuming two additional IH-DTL modules with this shunt impedance and each powered by a 200-kW solid-state RF amplifier, the muons can be accelerated from 4.26 MeV to 9.5 MeV before being injected into the DAW-CCL section.

The design of the DAW-CCL with muons injected at an energy of 9.5 MeV was carried out using SUPERFISH, PARMILA[29], and TRACE-3D[30]. Parameters such as the transit time factor were evaluated using SUPERFISH, as presented in[13], and then implemented into the beam dynamics calculations in PARMILA and TRACE-3D. Figure 5 shows the beam envelope calculation obtained with TRACE-3D. Due to the higher injection energy, the achievable acceleration gradient increases to 8.2 MV/m, whereas in the original configuration it was limited to 5.6 MV/m because of strong RF defocusing. The reduced phase spread resulting from phase damping at higher energies also allows the synchronous phase to be shifted from -30° to -20°, thereby increasing the effective acceleration gradient. With these improvements, muons can be accelerated up to 29 MeV using four DAW tanks (two tanks powered by each 2.5 MW klystron). In this configuration, the total DAW-CCL length and the number of accelerating cells are reduced to approximately one-third of the original design, and the required number of klystrons is reduced from three to two.

Table 1: Cell parameters for the IH-DTL to accelerate muons from 4.26 MeV to 7.25 MeV.

cell	W [MeV]	β	drift tube length [mm]	gap [mm]
entrance	4.26	0.28	-	51.0
1	4.53	0.28	76.5	52.5
2	4.80	0.29	78.8	54.0
3	5.08	0.30	80.9	55.4
4	5.37	0.31	83.1	56.9
5	5.66	0.31	85.3	58.3
6	5.96	0.32	87.4	59.7
7	6.27	0.33	89.5	61.1
8	6.59	0.34	91.6	62.5
9	6.92	0.35	93.7	63.9
10	7.25	0.35	95.8	65.2

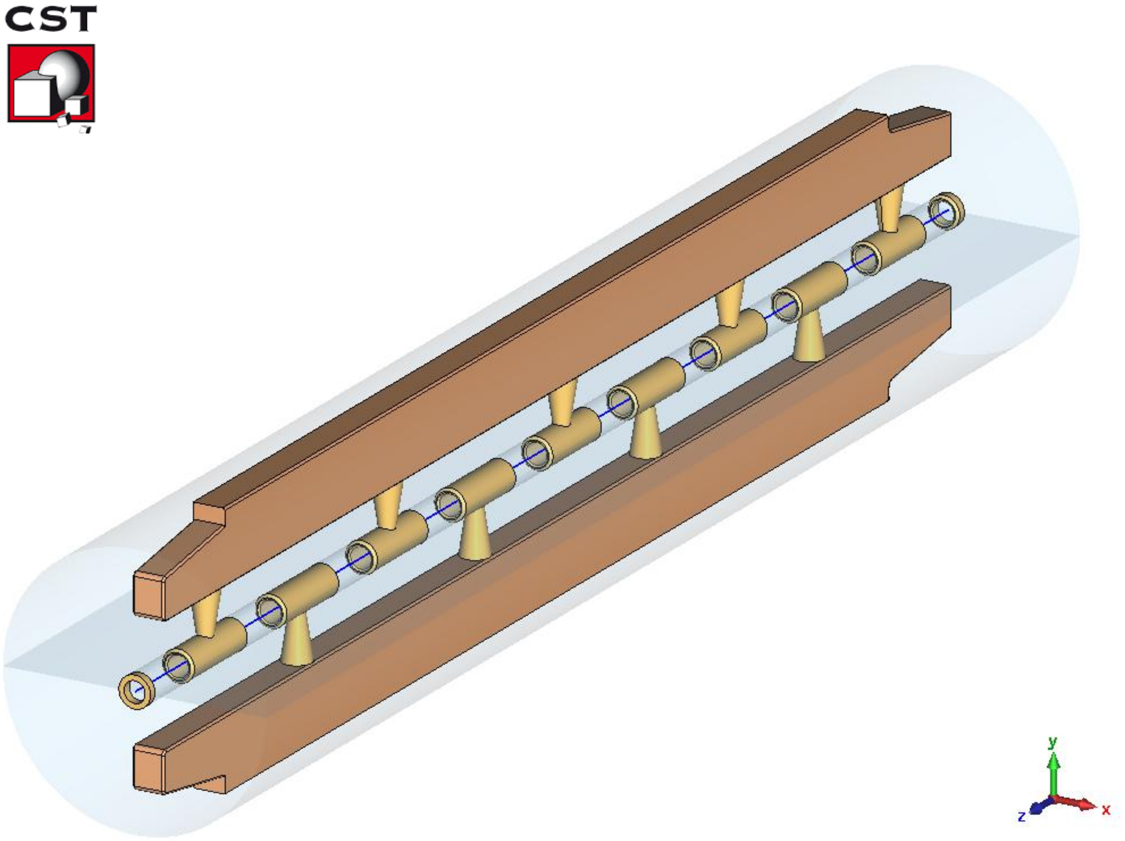
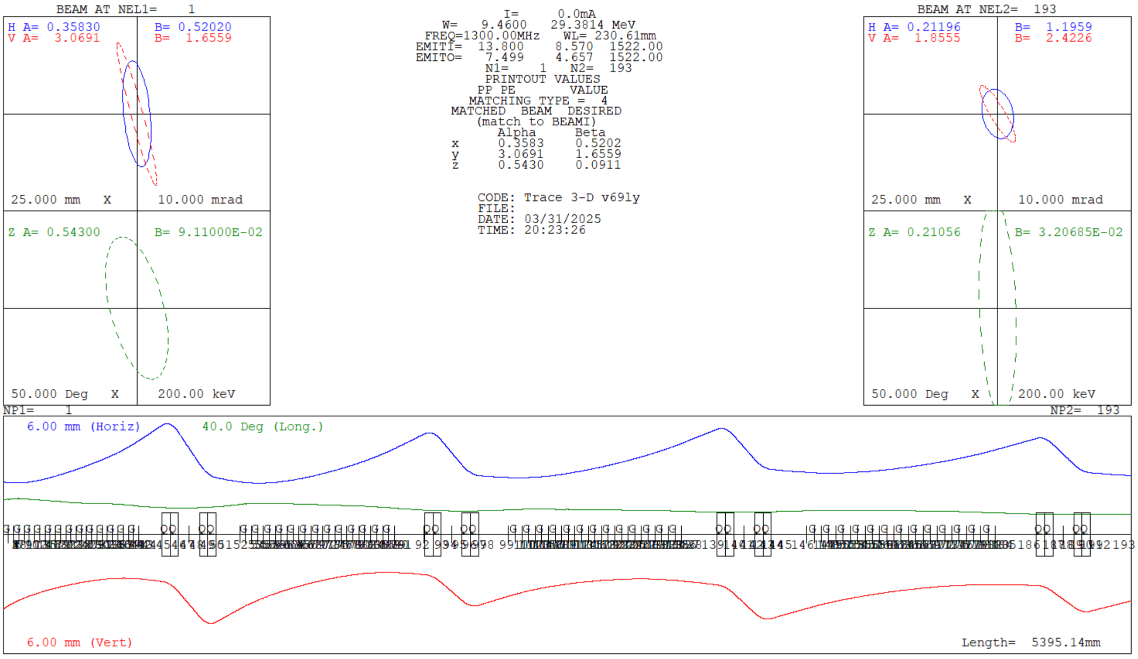


Figure 4: CST model of the additional IH-module to accelrate muons from 4.26 MeV to 7.25 MeV.

In response to the reduction of the injection energy into the DLS from 40 MeV to 29 MeV, a revised design of the DLS was also investigated. In the current design, four accelerating structures are operated using a 20 MW klystron to achieve acceleration gradients ranging from 19.6 to 21.4 MV/m. It was confirmed that, by lowering the acceleration gradient to 18.6–21.2 MV/m while maintaining the same RF power, acceleration from 29 MeV remains feasible. The corresponding increase in total DLS length is approximately 0.5 m, which is negligible when compared to the ≈10 m reduction achieved in the DAW-CCL section. In the revised configuration, the tank length becomes 2.3 m, approaching the maximum length supported by existing fabrication experience.



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 EMITO=   7.499    4.657  1522.00
          N1=    1   N2=  193
          PRINTOUT VALUES
         PP PE       VALUE
        MATCHING TYPE =  4
      MATCHED  BEAM  DESIRED
         (match to BEAMI)
            Alpha     Beta
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      y     3.0691    1.6559
      z     0.5430    0.0911

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Figure 5: Output of TRACE-3D envelope calculations for the IH1 tank.

4 CONCLUSION

A comprehensive study of the medium-velocity region in the muon linac was conducted to explore a more efficient configuration. The design study of the APS structure validated the choice of the DAW-CCL for this velocity region, confirming its high efficiency compared to APS. Furthermore, an alternative configuration that extends the upstream IH-DTL and downstream DLS sections was proposed and evaluated. This modification allows the DAW-CCL to be shortened to one-third of its original length, suggesting the possibility of a more efficient and cost-effective overall linac design. Further investigation, including detailed cavity design and optimization, will be carried out to realize this configuration.

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