Beam dynamics design of the muon linac high-beta section

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Abstract. A muon linac development for a new muon g-2 experiment is now going on at J-PARC. Muons from the muon beam line (H line) at the J-PARC muon science facility are once stopped in a silica-aerogel target, and room temperature muoniums are evaporated from the aerogel. They are dissociated with lasers, then accelerated up to 212 MeV using a linear accelerator. For the accelerating structure from 40 MeV, disk-loaded traveling-wave structure is applicable because the particle beta is more than 0.7. The structure itself is similar to that for electron linacs, however, the cell length should be harmonic to the increase of the particle velocity. In this paper, the beam dynamics design of this muon linac using the disk-loaded structure (DLS) is described.

1. 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). Currently, the most precise \((g - 2)_\mu\) experiment is E821 of Brookhaven national laboratory [1]. The precision is 0.54 ppm and the measured value indicates approximately three standard deviations from the SM prediction. 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 also can be measured with a precision of \(1 \times 10^{-21} e\cdot cm\) [2]. 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, 1000\(\pi\) 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 \(1.5\pi\) mm mrad. To satisfy this requirement, we are planning to use ultra-slow muons (USMs) generated by laser-dissociation of thermal muoniums \((\text{Mu}: \mu^+e^-)\) from a silica-aerogel target[3]. The room temperature USMs (25 meV) should be accelerated to 212 MeV to obtain the required \(\Delta p_t/p\). A linac realizes rapid acceleration required to accelerate muons, whose lifetime is very short (2.2\(\mu s\)). In Figure 1, the configuration of the muon linac [4] is shown.

The muon linac will be constructed at the H line [5] of the J-PARC muon science facility. The USMs are bunched and accelerated to 0.34 MeV by a radio frequency quadrupole linac (RFQ). Following the RFQ, an interdigital H-mode drift tube linac [6] is used to accelerate to
4.5 MeV. Then, muons are accelerated to 40 MeV through a disk and washer (DAW) coupled cavity linac (CCL) section. Because the accelerating gradient of the CCLs is typically less than 10 MV/m, the total length of the muon linac will exceed the available space of the J-PARC site if the muons are accelerated up to 212 MeV using a CCL: higher gradient is necessary. Above 40 MeV, the velocity $\beta$ of the muon is more than 0.7, therefore, a disk-loaded structure (DLS) traveling-wave (TW) linac is applicable. Another choice of the high gradient structure is a superconducting linac. However, the pulse width of our muon linac is short ($\sim 10$ ns), thus the power efficiency of the superconducting system will be very low. Moreover, the disk-loaded TW structure is quite mature technique widely used for electron linacs, therefore we chose this structure for the high-$\beta$ section. Table 1 summarizes the main parameters of the DLS section.

| Input energy | 40 MeV |
| Output energy | 212 MeV |
| Beam intensity | $1 \times 10^6$ /s |
| Beam pulse width | 10 ns |
| Number of bunches | 3 /pulse |
| Repetition rate | 25 Hz |
| Normalized transverse emittance | 1.5$\pi$ mm mrad |
| Momentum spread | 0.1% |

In this paper, present status of the beam dynamics design of the high-$\beta$ section (DLS section) of the muon linac is described.

2. Cell Design
Table 2 shows the assumed parameters of the accelerating tubes.

Because the muons are gradually accelerated compared to the electrons, cell length $D$ is varied cell by cell according to the velocity of the synchronous particle $\beta_s$. We adopt $2\pi/3$ mode operation, thus $D$ is derived as

$$D = \frac{\beta_s \lambda}{3}.$$  \hspace{1cm} (1)
Table 2. Assumed design parameters of the accelerating structure.

| Parameter                        | Value                  |
|----------------------------------|------------------------|
| Structure                        | Disk loaded traveling wave |
| Frequency                        | 1296 MHz               |
| Accelerating mode                | $2\pi/3$               |
| Accelerating tube length         | $\sim 2$ m            |
| Accelerating gradient            | 20 MV/m               |

Energy gain $\Delta W$ in one cell is determined as

$$\Delta W = E_0 D \cos \phi,$$

where $E_0$ is the accelerating gradient, and $\phi$ is the phase relative to the crest of the wave. In the current design, $\phi$ is set to be -10 deg. to assure enough longitudinal acceptance.

3. Structure Design

Design of the DLS is conducted by using a tool package for simulation of traveling-wave accelerating tubes [7]. This tool utilizes SUPERFISH [8] to determine the geometrical...
parameters of the structure. SUPERFISH generates the standing-wave-mode electric-field maps of each cell with open-open and short-short boundary conditions. The electric field of the traveling wave is represented by superposing these two maps with a phase difference of $\pi/2$, and used for particle simulation using General Particle Tracer (GPT) [9]. In this study, constant impedance design is adopted for simplicity, that is, the aperture radius $a$ is fixed as $2a = 40$ mm. As described in previous section, the calculated $D$ from $\beta_s$ is used as an input parameter. The inner diameters of each cell $2b$ is automatically tuned by the code to be 179.4 to 180.3 mm to obtain the desired resonant frequency with both boundary conditions.

![Figure 3. Structure parameters of the DLS1.](image)

Figure 3 shows the parameters of the first disk-loaded structure (DLS1) as an example. The $D$ is the input parameter, and $E_0$, shunt impedance per unit length $Z$, group velocity $v_g$, and quality factor $Q$ are the calculated values by using SUPERFISH.

4. Particle Simulation

Particle distribution obtained by the simulation of the DAW [4] is used for the DLS simulation. In the reference [4], matching between the DAW and DLS was not considered. In this study, matching parameters of the first DLS periodic unit is derived by using TRACE3D [10], as shown in Figure 4. One periodic unit consists of an accelerating tube and a doublet of quadrupole magnets.

To realize these matching parameters, a matching section with three quadrupole magnets is designed using TRACE3D, as shown in Figure 5. The particles are transported by using PARMILA [11], then the obtained particle distribution is inputted into the GPT simulation.
Figure 4. Injection matching of the DLS section using TRACE3D.

Figure 5. Matching section between the DAW and the DLS sections.

Figure 6 shows the phase-space distribution at the exit of the DLS section, and Figure 7 represents the transverse emittance evolution through the DLS section. Almost no emittance growth is observed. The transmission through the DLS section is 100%, and the loss due to the muon decay is estimated to be 1%. The horizontal and vertical normalized rms transverse emittances at the DLS exit are $\varepsilon_{x,n,\text{rms}} = 0.33\pi \text{ mm mrad}$ and $\varepsilon_{y,n,\text{rms}} = 0.21\pi \text{ mm mrad}$, respectively. The rms momentum spread is 0.04%. Table 3 is a summary of the DLS simulation.

The beam quality matches the requirements. However, one issue is that the shunt impedance of the accelerating tube is low due to the short cell length and large aperture. Therefore, the
Figure 6. Simulated particle distribution at the DLS exit. Lower right figure shows the momentum histogram.

Table 3. Result of the DLS simulation.

| Parameter          | Value       |
|--------------------|-------------|
| Transmission       | 100%        |
| Decay loss         | 1%          |
| $\varepsilon_{x,n,rms}$ | $0.33\pi$ mm mrad |
| $\varepsilon_{y,n,rms}$ | $0.21\pi$ mm mrad |
| Momentum spread    | 0.04%       |

The required power for one tube is approximately 80 MW; this is rather high for an actual RF system. Figure 8 shows the beam envelopes through the DLS section, and the vertical axis represents
the six times the rms beam width; all particles are within this envelope in this simulation. This figure shows that the aperture of the structure (a = 20 mm) has enough margin to the beam envelope. Thus, we expect to improve the shunt impedance by reducing the aperture. Also, the design will be improved by adopting the constant gradient structure. Moreover, considering the S-band structure is another possibility. We continue the design work to optimize the DLS system.

5. Summary
We conducted the beam dynamics design of the muon linac high-beta section. The first reference design is obtained and the simulated transverse emittances are $0.33\pi$ mm mrad and $0.21\pi$ mm mrad in horizontal and vertical phase space, respectively. The momentum spread is 0.04%. These parameters satisfy the requirement, however, the nominal RF power of the present design is rather high. We will do further improvement of the design.

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