BEAM DYNAMICS DESIGN OF THE MUON LINAC HIGH-BETA SECTION

Y. Kondo*, K. Hasegawa, JAEA, Tokai, Naka, Ibaraki, 319-1195, Japan
M. Otani, T. Mibe, M. Yoshida, KEK, Oho, Tsukuba, Ibaraki, 305-0801, Japan
R. Kitamura, Univ. of Tokyo, Hongo, Tokyo, 113-8654, Japan

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.

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 $1 \times 10^{-21} e{\cdot}\mathrm{cm}$ [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, 1000π 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 1.5π mm mrad. To satisfy this requirement, we are planning to use ultra-slow muons (USMs) generated by laser-dissociation of thermal muoniums (Mu: μ^+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 μs). In Figure 1, the configuration of the muon linac [4] is shown.

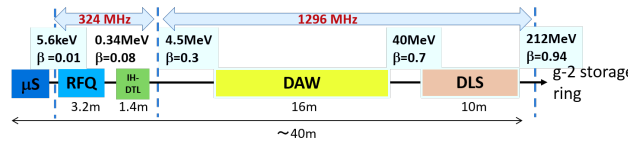

Figure 1: Configuration of the muon linac.

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 β 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 (~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-β section. Table 1 summarizes the main parameters of the DLS section.

Table 1: Main Parameters of the DLS Section

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

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

CELL DESIGN

Table 2 shows the assumed parameters of the accelerating tubes.

* yasuhiro.kondo@j-parc.jp

Copyright © 2017 CC-BY-3.0 and by the respective authors

Table 2: Assumed Design Parameters of the Accelerating Structure

Structure	Disk loaded traveling wave
Frequency	1296 MeV
Accelerating mode	$2\pi/3$
Accelerating tube length	~2 m
Accelerating gradient	20 MV/m

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 β_s. We adopt $2\pi/3$ mode operation, thus D is derived as

$$D = \frac{\beta_s \lambda}{3}. \quad (1)$$

Energy gain ΔW in one cell is determined as

$$\Delta W = E_0 D cos\phi, \quad (2)$$

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

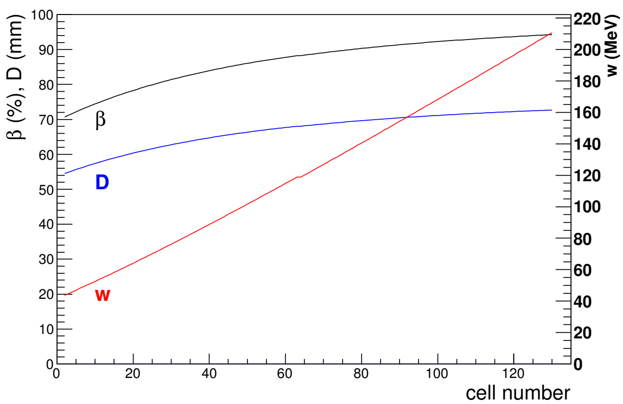

Figure 2: Calculated cell parameters of the DLS section.

Figure 2 shows the derived β, D, and the particle energy W through the DLS section as functions of the cell number. The disk-loaded stricture is designed using this D.

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 β_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.

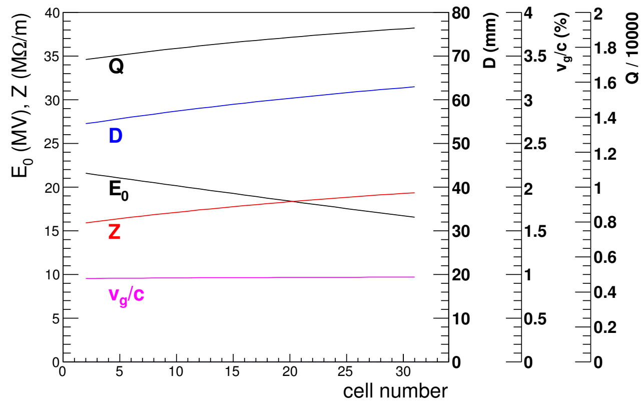

Figure 3: Structure parameters of the DLS1.

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.

PARTICLE SIMULATION

Particle distribution obtained by the simulation of the DAW [4] is used for the DLS simulation. In the ref. [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.

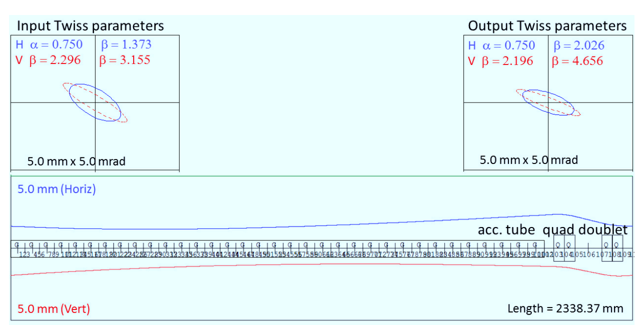

Figure 4: Injection matching of the DLS section using TRACE3D.

To realize these matching parameters, a matching section with tree 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.

Copyright © 2017 CC-BY-3.0 and by the respective authors

ISBN 978-3-95450-182-3

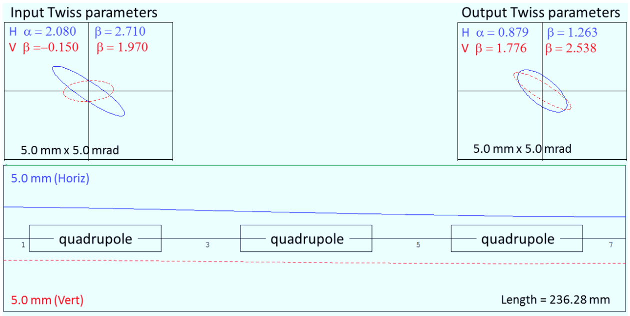

Figure 5: Matching section between the DAW and the DLS sections.

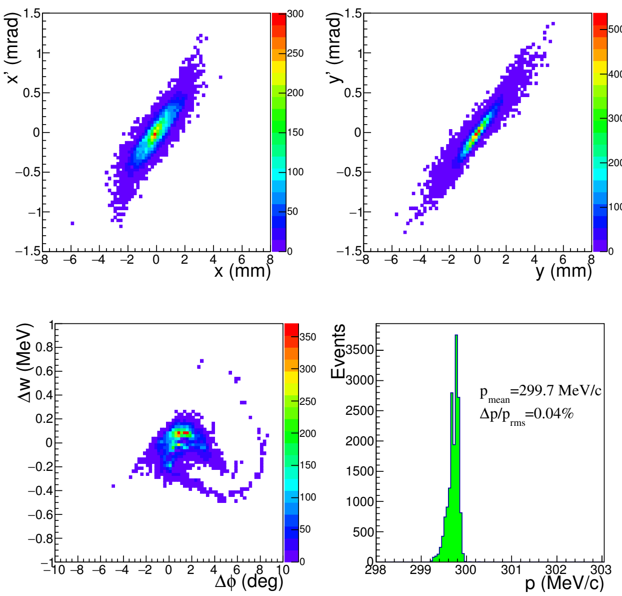

Figure 6: Simulated particle distribution at the DLS exit. Lower right figure shows the momentum histogram.

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 $\varepsilon_{x,n,rms}$ = 0.33π mm mrad and $\varepsilon_{y,n,rms}$ = 0.21π mm mrad, respectively. The rms momentum spread is 0.04%. Table 3 is a summary of the DLS simulation.

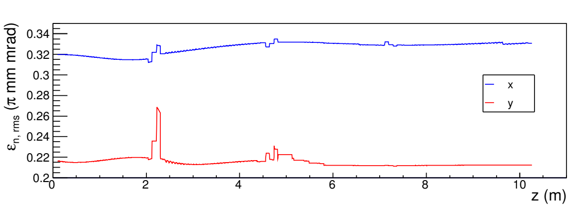

Figure 7: Emittance evolution through the DLS section.

Table 3: Result of the DLS Simulation

Transmission	100%
Decay loss	1%
$\varepsilon_{x,n,rms}$	0.33π mm mrad
$\varepsilon_{y,n,rms}$	0.21π mm mrad
Momentum spread	0.04%

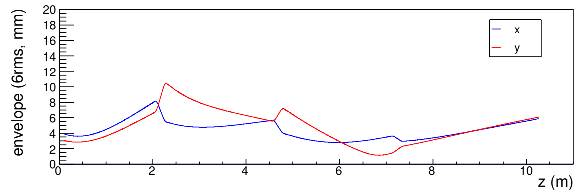

Figure 8: Beam envelope of the DLS section.

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 required power for one tube is approximately 80 MW; this is rather high for 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.

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 0.33π mm mrad and 0.21π 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.

ACKNOWLEDGMENT

This work is supported by JSPS KAKENHI Grant Numbers JP15H0366 and JP16H03987.

REFERENCES

[1] G. W. Bennett, et al., “Final report of the E821 muon anomalous magnetic moment measurement at BNL”, Phys. Rev. D 73 (2006) 072003.

[2] T. Mibe, edit., “J-PARC E34 conceptual design report”, Tech. rep., KEK (2011).

[3] P. Bakule, et al. , “Measurement of muonium emission from silica aerogel”, Prog. Theor. Exp. Phys. 2013 (103C01).

Copyright © 2017 CC-BY-3.0 and by the respective authors

[4] M. Otani, et al., “Development of muon linac for the g-2/EDM experiment at J-PARC”, Proceedings of LINAC2016, East Lansing, MI, USA, 2016, pp. 990–994.

[5] N. Kawamura, et al., “H line; A beamline for fundamental physics in J-PARC”, Proceedings of USM2013, 2014, p. 010112.

[6] M. Otani, et al., “Interdigital H-mode drift-tube linac design with alternative phase focusing for muon linac”, Phys. Rev. Accel. Beams 19 (2016) 040101.

[7] M. Yamamoto, (in Japanese) http://www.yamamo10.jp/yamamoto/study/accelerator/GPT/TW_structure/

[8] J. H. Billen, L. M. Young, “Poisson Superfish”, LA-UR-96-1834 (1996).

[9] Pulser Physics, “General Particle Tracer”, http://www.pulsar.nl/gpt/

[10] K. R. Crandall, D. P. Rusthoi, ”Trace 3-D Documentation”, LA-UR-97-886 (1997).

[11] H. Takeda, “Parmila”, LA-UR-98-4478 (1998).

Copyright © 2017 CC-BY-3.0 and by the respective authors

ISBN 978-3-95450-182-3