Compact buncher cavity for muons accelerated by a radio-frequency quadrupole

M. Otani,† Y. Sue,‡ K. Futatsukawa,§ T. Iijima, ¶ H. Iimura,∥ N. Kawamura,† R. Kitamura,∥ Y. Kondo,¶ T. Morishita,¶ Y. Nakazawa,∥ H. Yasuda,∥ M. Yotsuzuka,‡ N. Saito,∥ and T. Yamazaki†

†High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan
‡Nagoya University, Nagoya, Aichi 464-8602, Japan
∥Ibaraki University, Mito, Ibaraki 310-8512, Japan
¶Japan Atomic Energy Agency (JAEA), Tokai, Naka, Ibaraki 319-1195, Japan
§University of Tokyo, Hongo, Tokyo 171-8501, Japan
∥University of Tokyo, Hongo, Tokyo 171-8501, Japan

A buncher cavity has been developed for the muons accelerated by a radio-frequency quadrupole linac (RFQ). The buncher cavity is designed for \( \beta = v/c = 0.04 \) at an operational frequency of 324 MHz. It employs a double-gap structure operated in the TEM mode for the required effective voltage with compact dimensions, in order to account for the limited space of the experiment. The measured resonant frequency and unloaded quality factor are 323.95 MHz and 3.06 \times 10^6, respectively. The buncher cavity was successfully operated for longitudinal bunch size measurement of the muons accelerated by the RFQ.

I. INTRODUCTION

Muon linacs have been studied for their potential advantages in various branches of science. After the muons are cooled to thermal energy \([1, 2]\), the muons are accelerated to the specific energy required by an application. One of the applications of accelerated muon beams is the transmission muon microscope \([3]\), which is used in materials and life sciences. If the muons are accelerated up to 10 MeV, it enables three-dimensional imaging of living cells, which is impossible with the use of transmission electron microscope. Another application of the muon linac is the precise measurement of the muon anomalous magnetic moment \((g_{\mu} - 2)\) and electric dipole moment \(\mu_{\mu}\). The experiment was conducted at the J-PARC muon science facility (MUSE) \([21]\). The J-PARC MUSE provides a pulsed muon \((\mu^+)\) beam with a 25-Hz repetition rate. The muons are decelerated by an aluminum degrader, and some portions form negative muonium \((\text{Mu}^-)\), \(\mu^+ e^-\). The \(\text{Mu}^-\)s are extracted and accelerated to 5.6 keV by an electrostatic lens \([22]\). They are then injected into the RFQ and accelerated to 89 keV. Then, the accelerated \(\text{Mu}^-\)s are transported to a detector via a diagnostic beamline.

II. DESIGN AND FABRICATION

The buncher cavity is designed for measuring the longitudinal bunch size after acceleration with the RFQ. The experiment was conducted at the J-PARC muon science facility (MUSE) \([21]\). The J-PARC MUSE provides a pulsed muon \((\mu^+)\) beam with a 25-Hz repetition rate. The muons are decelerated by an aluminum degrader, and some portions form negative muonium \((\text{Mu}^-)\), \(\mu^+ e^-\). The \(\text{Mu}^-\)s are extracted and accelerated to 5.6 keV by an electrostatic lens \([22]\). They are then injected into the RFQ and accelerated to 89 keV. Then, the accelerated \(\text{Mu}^-\)s are transported to a detector via a diagnostic beamline.

Figure 1 shows the layout of the diagnostic beamline. In previous experiments for the demonstration of muon acceleration \([11]\) and profile measurement \([23]\), the diagnostic beamline consisted of a pair of quadrupole mag-
The function of the buncher cavity is to provide sufficiently large effective voltage for the longitudinal bunch size measurement, as required. A single-anode (SA) microchannel plate (MCP, Hamamatsu photonics F9892-21) and multi-anode (MA) MCP detectors are placed at the downstream end of the straight line and at $45^\circ$ line, respectively. The SA-MCP detector measures the penetrating muons $\mu^+$ for the beamline tuning. The MA-MCP detector is used for the longitudinal bunch size measurement. In order to focus the beam longitudinally, and measure the longitudinal beam properties, it is necessary to have a buncher cavity. Because there is a beam dump just after the detectors, the available space for the buncher cavity is approximately 150 mm.

The buncher cavity is designed using CST MW Studio. Figure 3 shows the cutaway of the three-dimensional model. The inner radius of the drift tube ($R_0$) is determined from the transverse beam size obtained from the simulations. The fillet radius of the drift tube ($R_{\text{fillet}}$) is tuned so that the operational frequency is 324 MHz. The cavity radius ($R_{\text{cav.}}$) is tuned so that the operational frequency is 324 MHz. The cavity dimensions are summarized in Table I.

The RF parameters obtained using CST MW Studio are summarized in Table II. The power needed to supply the required voltage is 0.21 kW, which is sufficiently small and satisfies the requirement.

In a QWR structure, a dipole field exists in the accelerating gaps. The dipole field effect on the beam dynamics is investigated by using GPT. The dipole field effect is negligible and the result is consistent to that obtained from PARMILA. Because the effect is negligible, conventional correction methods such as shifting the inner drift tube was not implemented.
FIG. 3. Cutaway view of the three dimensional model of the buncher cavity.

In the longitudinal bunch size measurement, it is not necessary to tune the resonant frequency to 324 MHz precisely; it is required to set the resonant frequency to the same value as that of the RFQ. In addition, there is no available space for a frequency tuning system such as a conductive tuner. Therefore, no frequency tuning system is implemented in the buncher cavity and the operation frequency of the RFQ is tuned to that of the buncher cavity.

The buncher cavity was fabricated using a three-piece design, as shown in Fig. 4. The two side plates are connected to the center plate via an RF contactor and a Viton O-ring. The drift tube and stem are machined in the center plate as a monolithic structure. The material of the cavity is oxygen-free copper (OFC, JIS C1020). The ISO KF40 duct and the side plate are attached by vacuum brazing. The transverse length of the buncher cavity is 450 mm, and the longitudinal length including the NW40 duct is 142 mm.

Figure 5 shows the fabricated center plate. Three-dimensional measurement after fabrication showed that the fabrication had an accuracy of approximately 0.05 mm. This fabrication error corresponds to 30 kHz.

FIG. 4. Mechanical structure of the buncher cavity.

FIG. 5. Center plate connected to a side plate.

| TABLE I. Cavity dimensions |
|-----------------------------|
| Dimensions | Values [mm] |
| $R_b$        | 16          |
| $R_a$        | 20          |
| $R_{fillet}$ | 1.5         |
| $L_{cav}$    | 40          |
| $L_{dtl}$    | 12          |
| $L_{gap}$    | 6.9         |
| $R_{1stem}$  | $\phi 15 - 20$ (ellipse) |
| $R_{2stem}$  | $\phi 6$    |
| $L_{stem}$   | 17.7        |
| $R_{cav}$    | 185.9       |

| TABLE II. RF parameters. |
|---------------------------|
| Parameters | Values |
| Frequency [MHz] | 324.01 |
| Effective voltage [kV] | 5.3 |
| $Q_0$ | $3.08 \times 10^3$ |
| $E_{pk}$ [MV/m] | 2.8 |
| Power dissipation [kW] | 0.21 |
| $R_{sh}$ [MΩ] | 0.13 |
III. RF MEASUREMENTS AND RESULTS

Measurements of the resonant frequency $f$ and the unloaded quality factor $Q_0$ were performed using a Vector Network Analyzer (VNA). Table III shows the measured and simulated values of $f$ and $Q_0$. The measured resonant frequency is in good agreement with the simulated one. The discrepancy of 0.02% between the measured and simulated frequencies is considered to be due to the effect of the loop-type of the RF pickup. The measured $Q_0$ is about 99% of the simulated one.

| Parameters       | simulation | measurement |
|------------------|------------|-------------|
| Resonant frequency (MHz) | 324.01     | 323.95      |
| Quality factor   | $3.08 \times 10^3$ | $3.06 \times 10^3$ |

Figure 6 shows a bead pull measurement setup [36]. A 3 mm diameter spherical metal bead on a fishing line is advanced by a motor driven pulley. The value of S21 is measured with the VNA while the metal bead is moving. The result of the phase shift measurement is shown in Fig. 7. The phase shift is proportional to $\varepsilon_0 E^2 - \mu_0 H^2/2$ [37], where $\varepsilon_0$ is the permittivity, $E$ is the electric field, $\mu_0$ is the magnetic permeability, and $H$ is the magnetic field. Two phase-shifting cycles are observed due to the double-gap. The measured phase shift along the z-direction is in excellent agreement with the simulated one. Especially around the gap, the difference is less than 4%, which is within the uncertainties of measurement due to the fishing line alignment and accuracy of the phase shift.

IV. CONCLUSION

A buncher cavity has been developed for the bunch size measurement after muon acceleration by the RFQ. It is designed for $\beta = 0.04$ with a frequency of 324 MHz. It employs a double-gap structure operated in the TEM mode to account for the limited space of the experiment.

The buncher cavity was designed using CST WM Studio. The cavity inner radius and total length are...
185.9 mm and 142 mm, respectively. It supplies an effective voltage of 5.3 kV with 0.21 kW for longitudinal bunch size measurement with compact dimensions.

Microwave and bead pull measurements were performed after fabrication. The resonant frequency was found to be in good agreement within 0.02%. The measured $Q_0$ was about 99% of the simulated one.

The buncher cavity was successfully operated for the longitudinal bunch size measurement of muons accelerated by the RFQ.

ACKNOWLEDGMENTS

We express our appreciation to TOTAL INTEGRATOR MACHINERY&ENGINEERING Co., who fabricated the buncher cavity. This work is supported by JSPS KAKENHI Grant Numbers JP16H03987, 18H05226, and JP18H03707. The experiment at the Materials and Life Science Experimental Facility of J-PARC was performed under user programs (Proposal No. 2018A0222).

[1] P. Bakule et al., Design and RF test of MEBT buncher cavities for C-ADS Injector II at IMP, [Nucl. Instru. Meth. B266, 335, 2008].
[2] G.A. Beer et al., Enhancement of muonium emission rate from silica aerogel with a laser-ablated surface, Prog. Theor. Exp. Phys. 091, C01, 2014.
[3] http://slowmuon.kek.jp/MuonMicroscopy_e.html
[4] http://g-2.kek.jp/portal/index.html
[5] Y. Kondo et al., High-power test and thermal characteristics of a new radio-frequency quadrupole cavity for the Japan Proton Accelerator Research Complex linac, Phys. Rev. ST Accel. Beams 16, 040102, 2013.
[6] Y. Kondo et al., Simulation study of muon acceleration using RFQ for a new muon g-2 experiment at J-PARC, Proc. of IPAC2015, 2015, THPP045, 2015.
[7] M. Otani et al., Interdigital H-mode drift-tube linac design with alternative phase focusing for muon linac, Phys. Rev. Accel. Beams, 19, 040101 (2016).
[8] M. Otani et al., Development of muon linac for the muon g-2/EDM experiment at J-PARC, in Proceedings of IPAC2016 (Busan, Korea, 2016) pp. 1543 - 1546.
[9] Y. Kondo et al., Beam dynamics design of the muon linac high-beta section, Journal of Physics: Conference Series 874, 012054 (2017).
[10] Y. Kondo, K. Hasegawa, and A. Ueno, Fabrication and Low-Power Measurement of the J-PARC 50-mA RFQ Prototype, in Proceedings of LINAC2006 (Knoxville, Tennessee USA, 2006) pp. 3898 – 3900.
[11] S. Bae et al., First muon acceleration using a radio frequency accelerator, Phys. Rev. Accel. Beams 21, 050101, 2018.
[12] Good, M.L., Phase-reversal focusing in linear accelerators, Phys. Rev. 92, 538, 1953.
[13] S. Mineaev and U. Ratzinger, APF or KONUS drift tube structure for medical synchrotron injectors – a comparison, in Proceedings of 1999 PAC Conf pp. 3555.
[14] Ki R. Shin et al., Double-gap rebuncher cavity design of SNS MEBT, in Proceedings of IPAC2012 (New Orleans, Louisiana, USA, 2006) pp. 3898 – 3900.
[15] Ki R. Shin et al., Feasibility of Folded and Double Dipole Radio Frequency Quadrupole (RFQ) Cavities for Particle Accelerators, IEEE Transactions on Nuclear Sciences, 61, 2 (2014).
[16] S. Huang et al., Design and RF test of MEBT buncher cavities for C-ADS Injector II at IMP, Nucl. Instru. Meth. A799, 44, 2015.
[17] Y. Yamazaki, “Technical Design Report of J-PARC” (KEK Report 2002-13); JAERI-Tech-2003-44
[18] H.M. Miyadere, A. J. Jason, K. Nagamine, Design of Muon Accelerators for an Advanced Muon Facility, in Proceedings of PAC 07 (Albuquerque, New Mexico, USA, 2007) pp. 3032-3034.
[19] J. S. Berg et al., Cost-effective design for a neutrino factory, Phys. Rev. Accel. Beams 9, 011001, 2006.
[20] M. Yoshida, et al., Re-acceleration of Ultra Cold Muon in J-PARC MLF, in Proceedings of IPAC’15 (Richmond, VA, USA, 2015) pp. 2533-2535.
[21] W. Higemoto, R. Kadono, N. Kawamura, A. Koda, K.M. Kojima, S. Makimura, S. Matoba, Y. Miyake, K. Shimomura and P. Strasser, Materials and Life Science Experimental Facility at the Japan Proton Accelerator Research Complex IV: The Muon Facility, Quantum Beam Sci. 2017, 1(1), 11.
[22] K.F. Cantor et al., in “Positron studies of solids, surfaces and atom” (World Scientific, Singapore, 1986) p. 199.
[23] M. Otani et al., Muon Profile Measurement After Acceleration With a Radio-Frequency Quadrupole linac, J. Phys. :Conf. Ser. 1067, 052018 (2018).
[24] Hamamatsu Photonics K. K., http://www.hamamatsu.com/
[25] Y. Sue et al., Development of the good time resolution monitor to measure the longitudinal structure of low-rate muon bunch for J-PARC E34 Experiment, in Proceedings of PASJ2018 (Nagaoaka, Japan, 2018) pp. 1051 – 1054.
[26] G4beamline, http://public.muonsinc.com/Projects/G4beamline.aspx
[27] R. Kitamura et al., First trial of the muon acceleration for J-PARC muon g-2/EDM experiment, Journal of Physics: Conference Series 874, 012055 (2017).
[28] Geant4, http://geant4.cern.ch/
[29] OPERA3D, Vector Fields Limited, Oxford, England., https://operafea.com/
[30] K. R. Crandall et al., “RFQ Design Codes,” LA-UR-96-1836 (1996).
[31] General Particle Tracer, Pulsar Physics. http://www.pulsar.nl/gpt/
[32] CST Studio Suite, Computer Simulation Technology (CST), https://www.cst.com/products/CSTWS
[33] K.R. Crandall and D.P. Rustoi, “TRACE 3D Documentation”, Los Alamos Report, No. LA-UR-97-886, 1997.
[34] Los Alamos Accelerator Code Group (LAACG), LANL, Los Alamos, http://www.laacg.lanl.gov
[35] P.N. Ostroumov, K.W. Shepard, Correction of beam-steering effects in low-velocity superconducting quarter-wave cavities, Phys. Rev. Accel. Beams 4 110101 (2001).
[36] Peter A. McIntosh, Perturbation Measurements on RF
Cavities at Daresbury.

[37] Klein, H., CERN Accelerator School on RF Engineering for Particle Accelerators, CERN 92-03, Vol. 1, 1992, p. 115.

[38] Tektronix Inc., http://www.tek.com/

[39] R & K Co. Ltd., http://www.rk-microwave.com/index.php