LOW-POWER TEST OF BRIDGE COUPLER CONNECTED TO TANK IN DISK-AND-WASHER STRUCTURE FOR MUON ACCELERATION

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Abstract

A muon linear accelerator is under development at the Japan Proton Accelerator Research Complex (J-PARC) for precise measurement of the muon anomalous magnetic moment ($g-2$) and search for the electric dipole moment (EDM). The disk-and-washer (DAW) structure is employed to accelerate muons from 30 % of the speed of light (kinetic energy = 4 MeV) to 70 % (40 MeV) at 1296 MHz. The muon DAW consists of tanks accelerating the muons and bridge couplers that couple the tanks and focus the beam using an internal quadrupole doublet. A bridge coupler prototype was fabricated and tested at low power. This low-power test focused on measuring resonant frequencies, Q-value, and electric field distribution. The measurements revealed an accelerating mode frequency deviation of −0.9 MHz from the simulation and a significantly degraded unloaded Q-value, reaching only about 65 % of the simulated value. Furthermore, the bridge coupler prototype was connected to a tank prototype and tested at low power to understand the effects of the connection. This paper summarizes these results and discusses the prospects for actual machine production.

INTRODUCTION

The muon anomalous magnetic moment ($g-2$) and the electric dipole moment (EDM) are highly sensitive probes for physics beyond the Standard Model. Regarding the $g-2$, while recent lattice QCD calculations improve agreement with experimental results, a tension remains between lattice QCD-based and data-driven evaluations, requiring further investigation [1–3]. Furthermore, the observation of an EDM directly implies time-reversal symmetry violation [4].

At the Japan Proton Accelerator Research Complex (J-PARC), an experiment is being prepared to measure the muon $g-2$ and search for the EDM using novel methods, including muon acceleration by a linear accelerator (linac). This four-stage linac employs a disk-and-washer (DAW) structure as its third stage to accelerate muons from 30 % of the speed of light (kinetic energy = 4 MeV) to 70 % (40 MeV) at 1296 MHz [5]. A DAW structure cavity, a type of coupled cavity linac, consists of disks, washers, and supporting stems. It was proposed in the 1970s [6] and later applied to protons [7]. It provides high shunt impedance for middle β and high electric field stability due to high coupling between accelerating cells and coupling cells.

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The muon DAW consists of alternating accelerating tanks and bridge couplers. The bridge couplers electromagnetically couple the tanks and provide space for beam focusing using an internal quadrupole doublet. Figure 1 shows an overview of the muon DAW. For the bridge coupler, a coaxial-type one was selected to take full advantage of the high coupling of the DAW structure. Figure 2 illustrates the configurations of the tank-bridge coupler.

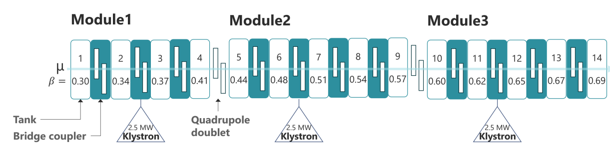

Figure 1: An overview of the muon DAW. The β shown in the figure represents the structure β (β_s) of each tank. The cell length within each tank is fixed according to its β_s.

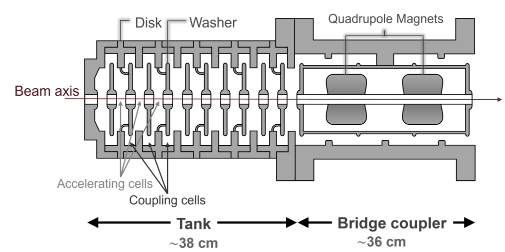

Figure 2: Cross-sectional view of the initial part of the muon DAW, cut vertically along the beam axis.

The development of the muon DAW began with the prototype fabrication of the first tank and bridge coupler. Because this initial section corresponds to the lowest particle velocity, it requires the narrowest accelerating gaps, presenting the most stringent fabrication challenges. A previous study reported the fabrication and performance evaluation of a tank prototype [8]. Also, a bridge coupler prototype was designed, fabricated, and was under evaluation [9]. This paper presents the low-power test results of this bridge coupler prototype, both individually and when connected to the tank prototype. The tests focused on measuring the resonant frequencies, Q-values, and electric field distributions.

DESIGN

The design of the bridge coupler prototype is shown in Fig. 3 and Table 1. This design satisfies all RF requirements, which include an accelerating mode resonant frequency of 1296.00 ± 0.01 MHz, a coupling mode frequency of 1296 ± 4 MHz, and an electric field flatness of 100 ± 1 %, defined as the ratio of the downstream peak amplitude to the upstream peak amplitude of the on-axis electric field. The detailed design process and final parameters are described in [9]. However, as a simplified prototype (shown in Fig. 4), it differs from the final production version in its material composition and omits the internal quadrupole magnet.

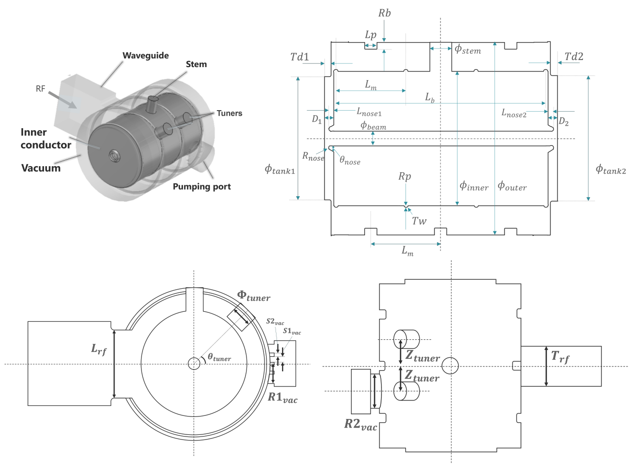

Figure 3: Cavity design. Top left: overall view. Top right: longitudinal cross-section. Bottom left: transverse cross-section. Bottom right: top view.

Table 1: Dimensions of the Most Upstream Bridge Coupler in the Final Design

Parameter	Value	Parameter	Value
L_b	329.197 mm	L_m	109.732 mm
ϕ_{stem}	34 mm	ϕ_{inner}	210 mm
ϕ_{outer}	300 mm	ϕ_{beam}	23.5 mm
ϕ_{tank1}	194.6284 mm	ϕ_{tank2}	196.7722 mm
Rp	2.82 mm	Lp	19.299 mm
T_w	Radius: 3.5 mm	R_b	10.69 mm
$Td1$	9.649 45 mm	$Td2$	11.57 mm
D_1	13.6 mm	D_2	15.9 mm
R_{nose}	2.6 mm	θ_{nose}	30°
L_{nose1}	8.304 mm	L_{nose2}	9.397 mm
L_{rf}	134 mm	T_{rf}	82.55 mm
Φ_{tuner}	40 mm	θ_{tuner}	45°
Z_{tuner}	54.8656 mm	$S1_{vac}$	17 mm
$S2_{vac}$	6 mm	$R1_{vac}$	46 mm
$R2_{vac}$	39 mm		

LOW-POWER TEST

In the low-power test, the accelerating mode resonant frequency, Q-value, and electric field distribution of the bridge coupler prototype were measured. However, because the coupling mode frequency could not be measured due to practical limitations in realizing the required boundary conditions in the actual apparatus, the present work provides only a partial RF validation of the standalone coupler. A Vector Network Analyzer was used for the measurements, and the electric field distribution was evaluated via the bead-pull method [10]. The experimental results were compared with simulations reflecting the actual measurement conditions, including antennas and other measurement components.

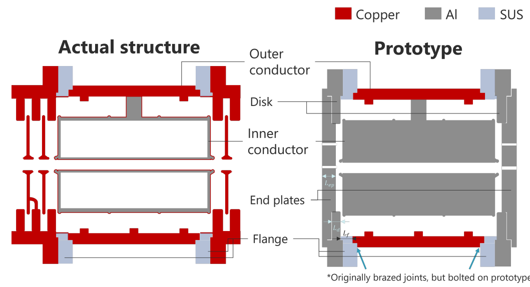

Figure 4: Bridge coupler prototype. The dimensions are L_{ep} = 33 mm, L_d = 10 mm, and L_f = 26.2 mm.

The measurement results are summarized in Table 2 and Fig. 5. The measured resonant frequency of the accelerating mode deviated from the target, failing to meet the requirement of ±0.01 MHz. Furthermore, the measured unloaded Q-value (Q_0) was significantly low, reaching only about 65 % of the simulated value. However, the measured electric field flatness showed good agreement with the simulation results.

Table 2: Measured vs. simulated RF properties. Measurements are corrected to the actual operating environment (vacuum, 30 °C). Uncertainties denote the standard deviation for measurements (omitted for single measurements) and mesh convergence for CST simulations [11].

Parameter	Measured	Simulated
Resonant frequency [MHz]	1294.7 ± 0.1	1295.6 ± 0.2
Q_0	3951	6184 ± 5
Electric field flatness [%]	101.4 ± 0.4	101.6 ± 0.5

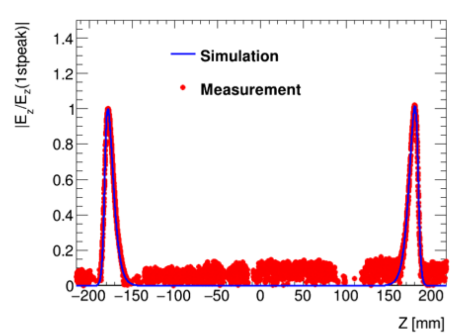

Figure 5: Electric field distribution along the beam axis.

DISCUSSION AND ADDITIONAL TESTS

Accelerating Mode Frequency and Tuner Study

The measured accelerating mode frequency was 0.9 MHz lower than the simulated value. To verify whether this discrepancy could be compensated, a sensitivity study was conducted using a simplified tuner in the coupled setup with a tank prototype (1 unit) on the upstream side. Although this temporary tuner lacks a precise adjustment mechanism, it allows for an insertion length of up to 15 mm. As shown in Fig. 6, the measured frequency shift at a 15 mm insertion length falls consistently between the simulated shifts for 10 mm and 20 mm. This level of agreement validates the accuracy of the model.

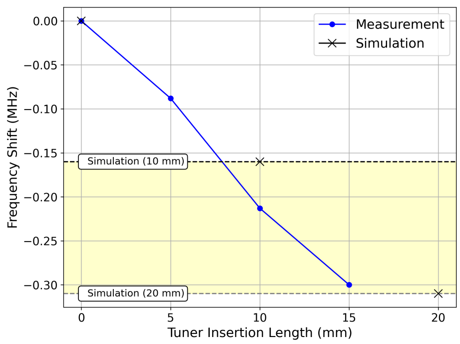

Figure 6: Frequency shifts vs. tuner insertion length.

Based on this validation, we evaluated the frequency correction capability for the final production version. The current design incorporates two tuners, each insertable up to 40 mm, providing a simulated total tuning range of 2.6 MHz. Given the demonstrated accuracy of the simulation model, the observed 0.9 MHz deviation is well within the compensation range of the production tuners.

Analysis of Q-value Degradation

The measured Q_0 was low, reaching only about 65 % of the simulated value. A probable cause is imperfect contact between the assembled structures. Because the prototype is mechanically bolted without RF O-rings, substantial contact resistance disrupts surface RF currents, increasing ohmic losses. Resolving this discrepancy remains a critical open issue; therefore, further investigation is required, alongside a re-evaluation using a model reflecting the final production specifications, which include brazing and copper plating.

Adjustment of Electric Field Flatness

The electric field flatness is highly sensitive to the axial position of the inner conductor; simulations predict a sensitivity of up to 34 % per 1 mm. To experimentally verify this relationship, measurements were performed by slightly varying the conductor's axial position, with displacements precisely tracked using a coordinate measuring machine (CMM). We confirmed that the flatness can be controlled this way, successfully matching simulations. However, manual iteration is impractical due to reproducibility and disassembly effort. Therefore, a precise axial positioning mechanism will be implemented in the actual cavity.

Connecting to the Tank

Furthermore, the same parameters were measured with the bridge coupler connected to a tank prototype (1 unit) upstream and an endcell (a terminating plate simulating a tank shape) downstream. However, it should be noted that the tank prototype used in this setup had known fabrication deviations, resulting in a resonant frequency shift and a degraded Q_0 during standalone measurements [12]. Consequently, the combined setup results likely reflect a combination of connection effects and inherent suboptimal tank performance. Therefore, the combined results should be regarded primarily as a preliminary integration test. The results are summarized in Table 3. Although a mode corresponding to the accelerating mode was identified, its resonant frequency did not meet the requirement, and the Q_0 exhibited a further decrease. Nevertheless, consistent with the measurement of the isolated bridge coupler, the electric field distribution was confirmed to be flat.

Table 3: Measured vs. Simulated RF Properties With the Tank Connection

Parameter	**Measured**	**Simulated**
Resonant frequency [MHz]	1297.3	1295.7 ± 0.1
Q_0	269.29	10 271 ± 9
Field flatness [%]	98.7 ± 1.1	99.8 ± 0.1

Future work will involve these measurements with a tank meeting the design specifications to accurately assess the connection's impact on the bridge coupler's performance.

CONCLUSION

This study demonstrated the fabrication of a bridge coupler prototype capable of exciting the required accelerating mode. Based on the low-power test results, several key prospects for the final production version were identified. The measured resonant frequency and Q_0 deviated from the simulated values. The frequency is expected to be corrected to the target value by implementing tuners with precise adjustment mechanisms. To address the Q_0 degradation, further investigation and re-evaluation using a model reflecting the final specifications are required. Furthermore, while the electric field flatness can be controlled by adjusting the inner conductor's axial position, a precise positioning mechanism will be introduced in the actual cavity to improve reproducibility. Finally, combined tests with a tank prototype excited the accelerating mode, but future evaluations must utilize a tank with verified RF performance to accurately assess the connection's impact.

ACKNOWLEDGMENTS

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