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Low-power test of bridge coupler in disk-and-washer structure for muon acceleration

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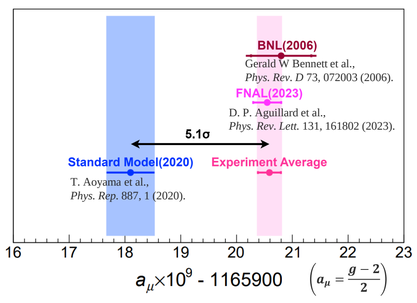
Abstract A muon linear accelerator is under development at J-PARC for precise measurement of the muon anomalous magnetic moment $g-2$ and electric dipole moment (EDM). A disk-and-washer (DAW) structure is employed to accelerate muons from 30% of the speed of light (kinetic energy = 4 MeV) to 70% (40 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 is currently being fabricated and will be tested. This paper presents the design and performance evaluation of the bridge coupler prototype.

Muon $g-2$/EDM

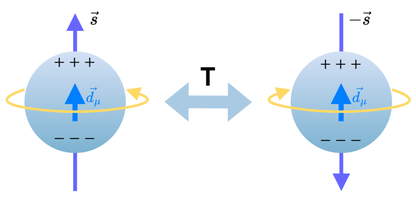
Anomalous Magnetic Moment ($g-2$)



Discrepancy between theoretical and experimental values

Sign of New Physics?

Electric Dipole Moment (EDM)

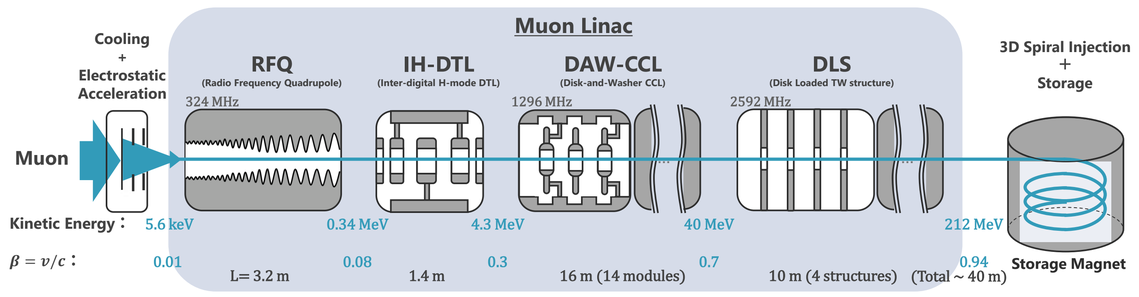


A physical quantity that breaks time-reversal symmetry

Observation = New Physics

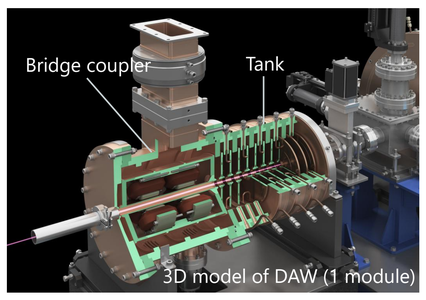
Measurement with muon linac @J-PARC

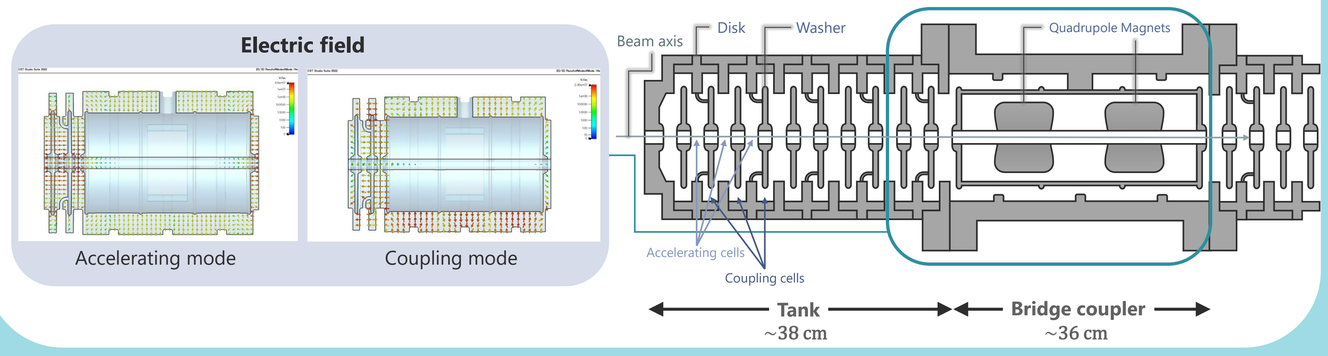
- Precise measurement of muon $g-2$/EDM by novel method. → Independent verification
- Novel method uses a low-emittance beam by muon cooling and reaccelerating.
- The muon linear accelerator (linac) consists of four stages suitable for $\beta(=v/c)$ and accelerates muons from $\beta = 0.01$ to 0.94.
- In 2024, the world's first cooled muon acceleration (up to 100 keV) was achieved (S. Aritome et al., *arXiv:2410.11367*, 2024).
- Furthermore, muon acceleration is an innovative technology with potential applications in muography and muon colliders in the future.



Disk-and-Washer (DAW) CCL

- Third stage ($\beta = 0.3$–0.7) of muon linac.
- A type of Coupled-Cavity Linacs (CCL)
- Bi-periodic structures
  - The frequencies of the accelerating mode excited in the accelerating cells and the coupling mode excited in the coupling cells must be matched.
- High power efficiency for middle β
- High cell-to-cell coupling due to co-axial coupling cells
  - High electric field stability
- It consists of accelerating tanks and bridge couplers that couple the tanks and focus the beam.



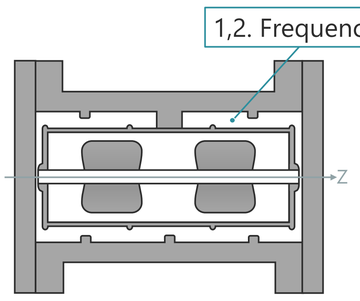


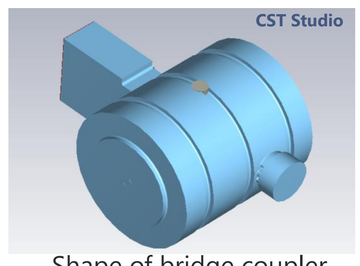
Bridge coupler development

- In a previous study, the tank prototype had completed the RF test and defined the basic geometry of the bridge coupler (Y. Takeuchi, *Ph.D. dissertation*, 2023).
  - Geometry satisfying beam dynamics and RF constraints.
- Few examples exist, so the bridge coupler needs to establish the fundamentals.
- We designed in detail (Fine-tuning, Ports installation) and fabricated a prototype.

Requirement

1. Accelerating mode frequency: $1296 \pm 0.1 + 1$ MHz (Due to cooling-water adjustability; Due to tuner adjustability)
2. Coupling mode frequency: 1296 ± 4 MHz
3. Field flatness of E_z/E_{ref} : $100 \pm 1\%$ (Due to beam dynamics)





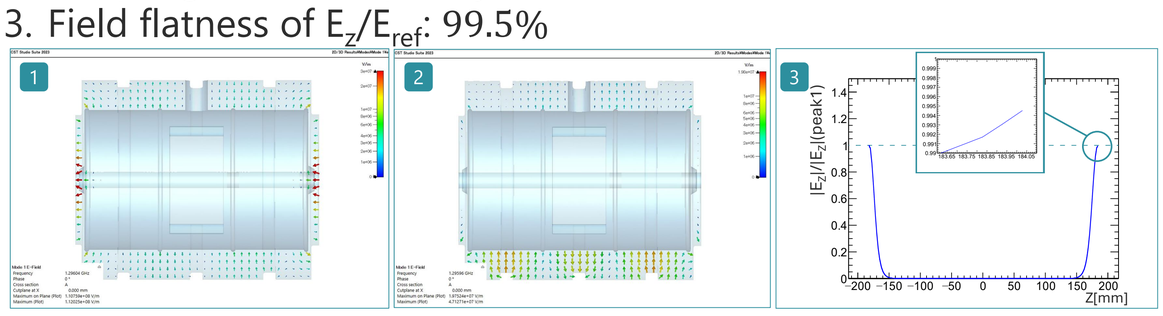
Shape of bridge coupler
*Blue region: Vacuum

Design

Simulation results of the final design

using CST Studio Suite (electromagnetic field simulation software)

1. Accelerating mode frequency: 1296.04 MHz
2. Coupling mode frequency: 1295.96 MHz
3. Field flatness of E_z/E_{ref}: 99.5%



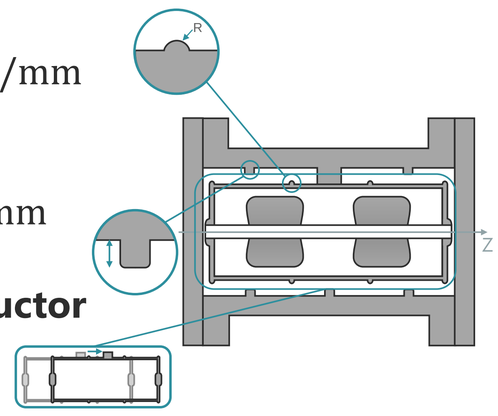
Achieved a design that satisfies the requirements.

Key parameters (selective to requirements)

Inner projection radius
Acceleration mode frequency: −7 MHz/mm
Requirement accuracy: < 0.1 mm

Outer projection length
Coupling mode frequency: −11 MHz/mm
Requirement accuracy: < 0.4 mm

The axial position of the inner conductor
Electric field flatness: 33%/mm
Requirement accuracy: < 0.03 mm



Fabrication and low-power test

Fabrication accuracy(absolute differences between design and measured values)

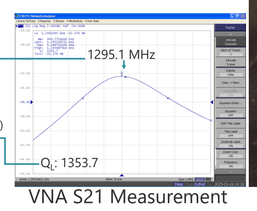
Inner projection radius: $< (7.7 \pm 0.05) \times 10^{-2}$ mm
Outer projection length: $(5 \pm 0.5) \times 10^{-4}$ mm
Satisfy requirements accuracy
The axial position of the inner conductor: in progress

RF characteristics

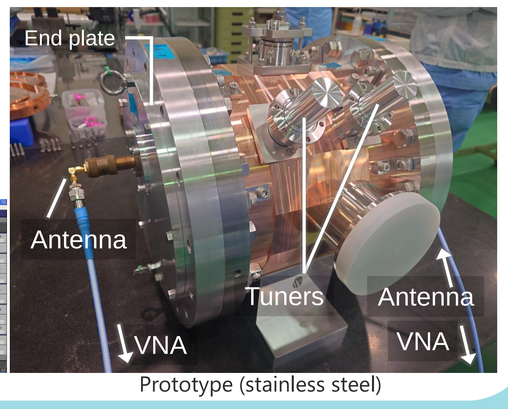
The evaluation was done with end plates, 2 antennas and a vector network analyzer (VNA).

Accelerating mode frequency
Simulation(w/ end plates): 1296.3 MHz
Measured: 1295.4 ± 0.3 MHz

Q-value
Simulation(w/ end plates): 8000
Measured: 3493



VNA S21 Measurement



Prototype (stainless steel)

Outlook

- The frequency was consistent with the simulation within 1 MHz.
- The remaining discrepancies are currently under investigation.
- Further studies, such as bead-pull measurements combining the tank and bridge coupler prototypes, are also being considered.