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FABRICATION OF THE PROTOTYPE SPOKE CAVITY FOR THE JAEA-ADS LINAC

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Abstract

Japan Atomic Energy Agency (JAEA) has been proposing an accelerator-driven nuclear transmutation system (ADS) to efficiently reduce high-level radioactive waste generated in nuclear power plants. As a first step toward the practical design of the JAEA-ADS linac, we are currently prototyping a low-β ($\approx$0.2) single-spoke cavity. The fabrication process for the prototype spoke cavity was investigated in fiscal year 2019, and the actual cavity fabrication started in 2020. Most of the cavity parts were shaped in fiscal year 2020 using press-forming and machining. We started joining the shaped cavity parts together by electron-beam welding in 2021, and the major three parts, the body and two lids, were fabricated through fiscal year 2023. In 2024, we adjusted the resonance frequency of the cavity by trimming the ends of the cavity parts. The cavity fabrication was finally completed by circumferentially welding the body and two lids together in fiscal year 2024.

INTRODUCTION

JAEA has been proposing an ADS as a future nuclear system to efficiently reduce high-level radioactive waste generated in nuclear power plants. In the ADS, long-lived nuclides are transmuted into short-lived or stable ones. One of the key R&D subjects for realizing the ADS is the reliability of the accelerator [1, 2]. In the JAEA-ADS, a high-power proton beam of 30 MW with a final energy of 1.5 GeV is required with high reliability. Since the accelerator needs to be operated in CW mode, a superconducting (SC) linac would be a suitable solution. The latest design of the JAEA-ADS linac is reported in Refs. [3, 4]. As shown in Fig. 1, the proposed linac consists of a normal-conducting radio-frequency quadrupole (RFQ), half-wave resonator (HWR), low-β and high-β single-spoke resonators (SSR1 and SSR2, respectively), and low-β and high-β elliptical cavities (ELL1 and ELL2, respectively).

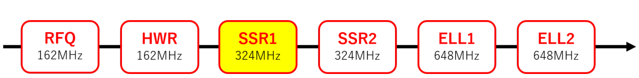

Figure 1: Proposed acceleration structure of the JAEA-ADS linac.

As a first step toward the practical design of the JAEA-ADS linac, we have decided to prototype the low-β ($\approx$0.2) single-spoke cavity, and conduct a high-field performance test of the prototype spoke cavity at liquid helium temperature. This prototyping will provide various insights on the development of SC cavities with TEM $\lambda/2$-mode resonance. In addition, the high-field cavity testing will provide valuable information such as how much field gradient can be achieved with reasonable stability. Therefore, both prototyping and performance-testing are essential to ensure the feasibility of the JAEA-ADS linac. In this paper, the fabrication of the prototype spoke cavity for the JAEA-ADS linac is presented.

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CAVITY DESIGN

The prototype spoke cavity with an operating frequency of 324 MHz was designed by electromagnetic simulation [5], and its dimensional parameters were optimized for higher cavity performance [6–8]. Figure 2 shows the cross-sectional views of the designed cavity with surface electric and magnetic field distributions. The cavity's design parameters are listed in Table 1. A multipactor analysis of the designed cavity without coupler ports is presented in Ref. [7].

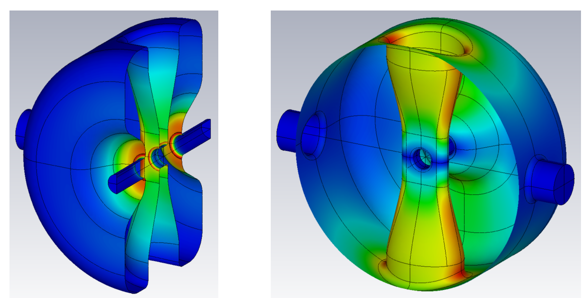

Figure 2: Cross-sectional views of the designed cavity with surface electric (left) and magnetic (right) field distributions.

Table 1: Design Parameters of the Prototype Spoke Cavity

Parameter	**Value**
f_0	324 MHz
β_g	0.188
β_{opt}	0.24
Beam aperture	40 mm
Cavity diameter	498 mm
Cavity length	300 mm
$L_{eff} = \beta_{opt}\lambda$	222 mm
$G = Q_0 R_s$	90 Ω
$T(\beta_{opt}) = V_{acc}/V_0$	0.81
$r/Q = V_{acc}^2/\omega U$	240 Ω
E_{peak}/E_{acc}	4.1
B_{peak}/E_{acc}	7.1 mT/(MV/m)

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FABRICATION THROUGH FY2023

The fabrication process of the prototype spoke cavity was investigated in fiscal year 2019, and the actual cavity fabrication started in 2020. The prototype spoke cavity is made of pure niobium (Nb), except for the niobium-titanium alloy (Nb-Ti) flanges for the RF ports and beam ports. These materials were provided by Tokyo Denkai Co., Ltd. Most of the cavity parts were shaped in fiscal year 2020 using press-forming and machining. The major parts were press-formed from 3.5 mm thick Nb sheets. The nose-shaped end drift-tubes (EDTs) and the port flanges were machined from Nb and Nb-Ti cylindrical blocks, respectively. The shaped cavity parts are shown in Figs. 9–11 of Ref. [8].

We started joining the shaped cavity parts together by electron-beam welding (EBW) in 2021. Before welding the actual cavity parts, each welding condition such as EBW beam parameters was carefully investigated using mock-up test pieces made of Nb or Nb-Ti. Furthermore, each joint to be welded was acid-cleaned (chemically polished), prior to each EBW, to remove impurities. The body section was mostly fabricated in fiscal year 2021 [9], and the beam port sections were fabricated in fiscal year 2022 [10]. In fiscal year 2023, the lid sections were fabricated, and the drift-tube (DT) electrode was welded to the spoke center of the body section [11]. Figure 3 shows the configuration of the major three parts fabricated through fiscal year 2023. To date, no welding defects, such as non-penetration, holes, spatters or pits, have been identified.

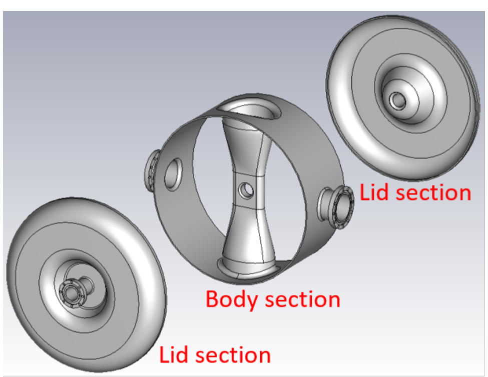

Figure 3: Configuration of the major three parts fabricated through fiscal year 2023.

FABRICATION IN FY2024

In fiscal year 2024, the cavity fabrication was scheduled for completion by circumferentially welding the body and two lids together. The fabrication history in fiscal year 2024 with the cavity-parts length is listed in Table 2.

Frequency Adjustment

Before welding the body and two lids together, we adjusted the resonance frequency of the cavity by trimming

Table 2: Fabrication History in Fiscal Year 2024 with the Length of Body and Lids

	Body (mm)	**Lids (mm)**
	217.0	59.0 ×2
Mechanical polishing		
Frequency meas. (May 1)		
Chemical polishing (Aug. 8)		
Frequency meas. (Sep. 10)		
1st trim (Oct. 7-8)	205.0	
Frequency meas. (Oct. 10)		
2nd trim (Nov. 13-14)	189.0	
Frequency meas. (Nov. 18)		
3rd trim (Dec. 9-10)	182.4	58.0 ×2
Frequency meas. (Dec. 12)		
Thinning (Dec. 23-24)		
Chemical polishing (Jan. 21)		
EBW of body and lid “a” (Jan. 28)		
Chemical polishing (Feb. 14)		
EBW of body and lid “b” (Feb. 21)		

the ends of the cavity parts. The cavity parts, particularly the body section, had been fabricated longer in the longitudinal direction than the design dimension to allow for the frequency adjustment during fabrication. The longitudinal length of the cavity has been shortened through three times of machining. The resonance frequency at each cavity length was measured by temporarily assembling the cavity from the body and two lids using indium wires (ϕ1 mm) to ensure electrical contact between them. Before the frequency measurement on May 1, weld beads on the inner side of the cavity were ground and smoothed by mechanical polishing. Before the freqnency measurement on Sep. 10, the entire surfaces of the body and two lids were chemically polished to a depth of approximately 10 μm. Figure 4 shows the measured

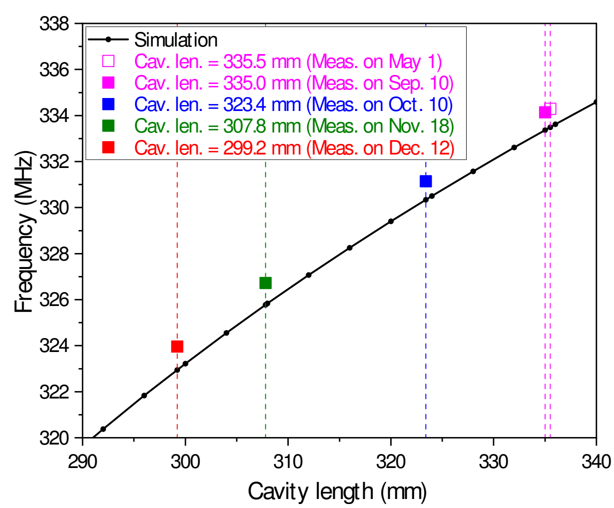

Figure 4: Measured freqnency at each cavity length.

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frequency converted in a vacuum taking into account the humidity effect [12]. The difference between the frequencies obtained by measurement and those obtained by simulation using the design dimension is primarily attributed to a reduction in EDT heights, resulting in an increase in the length of the acceleration gaps, due to welding shrinkage.

EBW Assembly of Body and Lids

The circumferential (≈ ϕ500 mm) welding requires weld beads inside the cavity to be sufficiently smooth, because we cannot access them for mechanical polishing after the final EBW assembly. In order to ensure smooth welding underbead, the parts to be welded must mate properly. It means that in the welding, not only the gap but also the step between the parts must be small enough. Therefore, the circularity of the weld joints of the cavity parts is very important for the precise alignment.

We measured the circularity of body ends (1), (2) and ends of two lids (lid “a” and lid “b”) by three-dimensional measurement. The design values for the inner and outer radii of the parts ends are 249.0 mm and 252.5 mm, respectively. The measurement revealed that the circularity of the body was insufficient compared to those of the two lids (Figs. 5 and 6). This would be because the body was EBW-assembled from four parts (two body sides and two spoke roots) while each end plate was press-formed from a single Nb sheet. Therefore, we decided to temporarily correct each body end for circularity by pressing it from the outside using a dedicated jig. As shown in Fig. 5, this correction allowed for a thickness of 2.0 mm: inner and outer radii of 249.5 mm and 251.5 mm, respectively. The thickness reduction is also preferred for less excess welding underbead. After the final (third) trimming for the frequency adjustment, the thickness of the parts ends were reduced using a machining center from 3.5 mm to 2.0 mm within a range of 5.0 mm from the end. Each body end was machined with circular correction using the dedicated jig. Since the two lids are sufficiently circular, the ends of the lids were machined without circular correction.

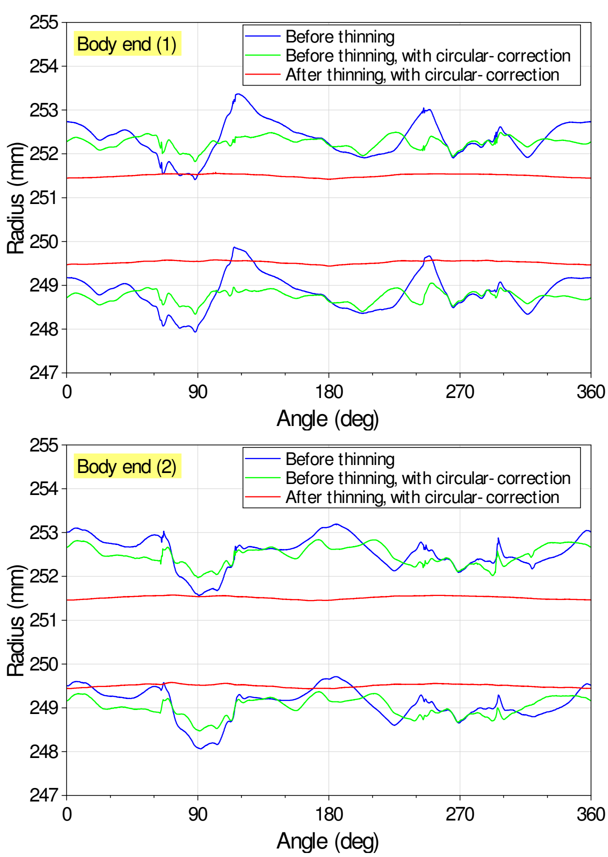

Figure 5: Angular distribution of the radii of body end (1) and (2) measured before and after the thickness reduction.

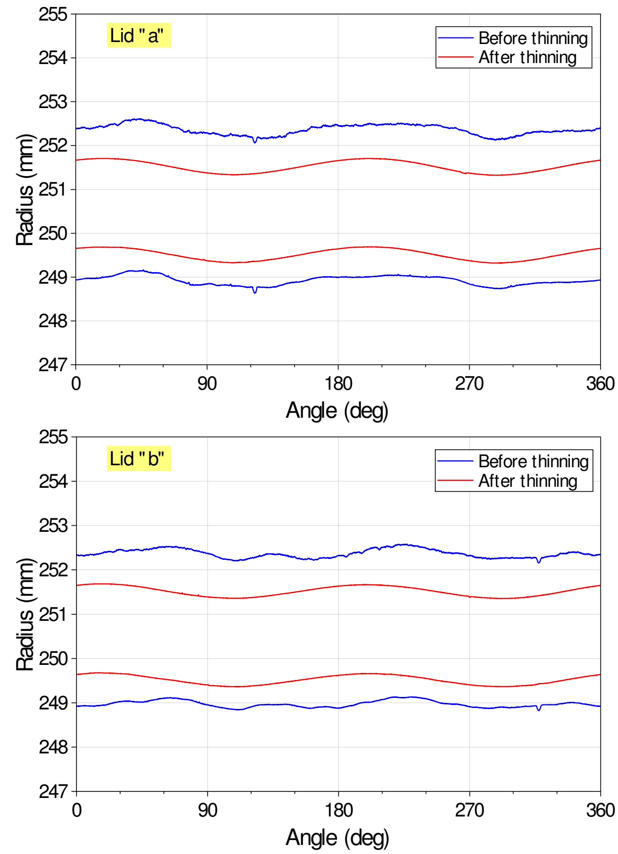

Figure 6: Angular distribution of the radii of lid “a” and “b” measured before and after the thickness reduction.

The body and two lids were finally joined together by the circumferential welding; body and lid “a” on Jan. 28, body and lid “b” on Feb. 21. The optimal EBW condition was carefully examined using ring-shaped Nb test pieces with inner and outer radii of 249.5 mm and 251.5 mm, respectively. Before each actual welding, the entire surfaces of the cavity parts were chemically polished to a depth of approximately 10 µm. During each welding, the circular shape of the body end was corrected to match that of the lid using the dedicated jig, minimizing the step between the two parts. At the same time, the gap between the two parts

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was eliminated using a welding fixture. Figure 7 shows the EB-welded body and lid "a", and Fig. 8 shows the fabricated spoke cavity. After the final EBW assembly, we visually inspected the inner side of the cavity through two RF ports and confirmed that smooth weld beads had been achieved. It was also confirmed that there were no vacuum leaks by actually evacuating the cavity using a fixing jig to suppress the inward pull of the beam ports.

Figure 7: Inside view of the EB-welded body and lid "a".

Figure 8: Fabricated spoke cavity.

SUMMARY

We have been prototyping the low-β ($\approx$0.2) single-spoke cavity. In 2024, we adjusted the resonance frequency of the cavity by trimming the ends of the cavity parts. The cavity fabrication was finally completed by circumferentially welding the body and two lids together in fiscal year 2024. In order to ensure the feasibility of the JAEA-ADS linac, performance evaluation of the fabricated cavity is imperative. Therefore, we are now proceeding with surface treatment of the cavity, and also preparing for a high-field performance test at liquid helium temperature.

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