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DEVELOPMENT OF SINGLE-SPOKE CAVITIES FOR ADS AT JAEA

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Abstract

Japan Atomic Energy Agency (JAEA) has been proposing an accelerator-driven system (ADS) as a future nuclear system to efficiently reduce the high-level radioactive waste generated at nuclear power plants. As the first step toward the full-scale CW proton linac for the JAEA-ADS, we are now prototyping a low-beta (around 0.2) single-spoke cavity. Because there is little experience in manufacturing superconducting spoke cavities in Japan, prototyping and performance testing of the cavity are essential to ensure the feasibility of the JAEA-ADS. The dimensional parameters of the prototype spoke cavity were optimized to obtain higher cavity performance. The actual cavity fabrication started in 2020. Most of the cavity parts were fabricated in the fiscal year 2020 by press forming and machining. In 2021, we started welding the cavity parts together. After investigating the optimum welding conditions using mock-up test pieces, each cavity part was joined with smooth welding beads. Currently, the cavity's body section and the beam port sections have been assembled. This paper presents the current status of the JAEA-ADS and it's cavity prototyping.

INTRODUCTION

Toward the realization of a sustainable society, nuclear energy has been gathering attention again in recent years, and expectations for new nuclear power systems such as small modular reactors and high temperature gas cooled reactors are increasing. However, the essential problem of generating spent nuclear fuel still exists. In addition, spent fuel that has already been generated must eventually be disposed of, therefore, the disposal of high-level radioactive waste is a common issue to all humankind that must be overcome. In Japan, the OMEGA project has been launched in 1998. Since then, the Japan Atomic Energy Agency (JAEA) has been pursuing the possibility of reducing the volume and toxicity of high-level waste through transmutation using an accelerator-driven subcritical reactor system (ADS) [1]. The purpose of the OMEGA project is the partitioning and transmutation (PT) of long-lived nuclear waste. The JAEA's proposal is, by PT of minor actinoides (MA), to reduce the area needed for geological disposal to 1/200, and to reduce the necessary years to lower the toxicity of the high-level waste below the natural uranium level from 100,000 to 300 years.

Figure 1 shows the schematic view of the JAEA-ADS subcritical reactor, and Table 1 summarizes the specifications of the JAEA-ADS. The transmission rate of 10%MA / year means that one ADS can transmute the MA from ten units of light water reactor. The essential difference between the ADS and conventional nuclear systems is that the proton beam from the accelerator controls the criticality of the reactor. The driver linac is the key component of the ADS.

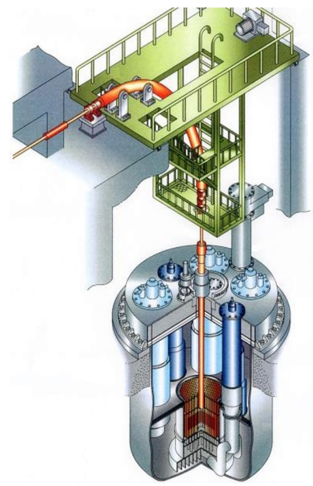

Figure 1: Schematic view of the JAEA-ADS subcritical reactor.

Table 1: Specifications of JAEA-ADS

Spallation target	Pb-Bi eutectic (LBE)
Coolant	LBE
Thermal output	800 MWt
Proton beam power	30 MW
Subcriticality k_{eff}	0.97
MA initial inventory	2.5 t
Transmutation rate	10%MA / year = 250 kg

During the 1990s, JAEA designed the first ADS linac [2] as a part of the Neutron Science Project (NSP). The NSP was designed to be a multipurpose neutron source that could also be used for ADS research and development. The accelerator had a beam current of 10 mA, a final energy of 1.5 GeV, and used normal conducting (NC) cavities in the low-medium relativistic β range of 0.06 (2 MeV) to 0.42 (100 MeV), as well as super conducting (SC) cavities in the high-β section. Later, the NSP was combined with the Japan Hadron Project (JHP) to become the J-PARC. The J-PARC linac achieves the final energy using NC cavities rather than SC cavities.

Based on the recent progress of low-β SRF technologies, we modernized the linac design from the NSP linac to match the requirement of the ADS dedicated linac listed in Table 2.

We decided to use SRF cavities for low-β region. However, in Japan, there is very little experience in the development of low-β SRF cavities, especially, never completed

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Table 2: Requirements for the JAEA-ADS Linac

Particle	proton
Energy	1.5 GeV
Beam current	20 mA
Duty factor	100% (CW)
Beam power	30 MW
Tolerable trip rate [3]	
≤ 10 s	20,000 /year
10 s ~ 5 min	2,000 /year
> 5 min	42 /year

spoke cavity. Therefore, we launched a prototyping project of the spoke cavities.

In this paper, the present progress on the development of the ADS linac, especially the prototyping of the spoke cavity is described.

LINAC DESIGN

In comparison to the NSP linac, the beam current of the ADS linac is doubled. Consequently, the main linac section, that is, from 2.5 MeV to 1.5 GeV region, must be completely redesigned. Figure 2 shows the configuration of the NSP linac planned in the 1990s [2].

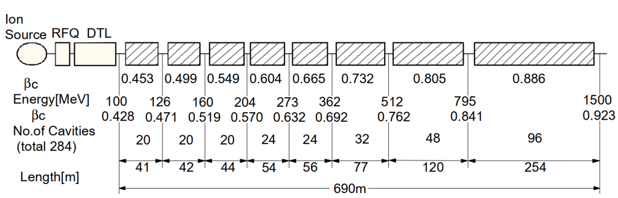

Figure 2: Configuration of the NSP linac planned in 1990s [2].

Figure 3 shows the current reference design of the JAEA-ADS linac, and Table 3 is the summary table of the SRF cavities for this design [4].

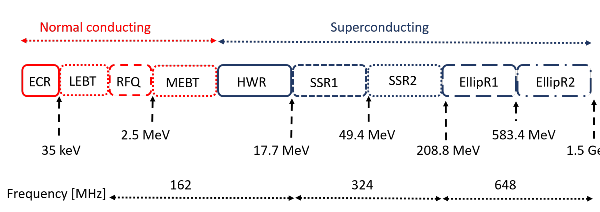

Figure 3: Configuration of the re-designed JAEA-ADS linac.

The drift tube linac (DTL) was changed to the half wave resonators (HWRs) and single spoke resonators (SSRs). The eight different elliptical resonator (EllipR) families were reduced to two, and the energy transitions between different β sections were optimized to reduce the number of cavities. Because of the available resources and our experience in the J-PARC linac, we chose the frequencies of 162, 324 and 648 MHz (the fundamental frequency of the J-PARC linac is 324 MHz). For the compatibility with fault compensation scheme [5], the maximum accelerating gradients were taken to be conservative levels.

Table 3: JAEA-ADS linac cavity parameters. The N_{cav} and N_{cryo} mean the numbers of the cavities and cyromodules, respectively.

Parameters	HWR	SSR1	SSR2	EllipR1	EllipR2
f_0 (MHz)	162	324		648	
β_g	0.08	0.16	0.43	0.68	0.89
N_{cell}		2		5	
Aper. (mm)		40		80	94
max. E_{acc} (MV/m)	7	7	8	14	14
N_{cav}	25	66	72	60	70
N_{cryo}	3	33	24	20	14

For this linac design, the modern strategy of linac design was fully implemented, especially, the equipartitioning scheme [6] was applied to whole the space-charge dominated SRF linac. Table 4 summaries the design results of the JAEA-ADS MEBT and SRF main linac. A compact and extremely low beam-loss linac design has been established.

Table 4: Design result of the JAEA-ADS linac (MEBT and main linac). Beam loss and emittance growth are simulation results with static errors and orbit correction [4].

Length	416 m
Number of cavities	295[a]
Number of cryomodules	94
Number of magnets	157
Input beam current	20 mA
Input transverse emittance	0.20 π mm mrad
Input longitudinal emittance	0.07 π MeV deg
Beam loss	3.5×10^{-3}%
Transverse emittance growth	1.5
Longitudinal emittance	1.3

[a] Including two MEBT bunchers

PROTOTYPE SPOKE CAVITY DESIGN

In parallel with the renewal of the linac design, the prototyping of the spoke cavity has started. We decided to make a prototype of SSR1, the lower β SSR of the two SSRs. The cavity design was conducted using CST Micro Wave Studio [7] to optimize the cavity performance [8]. Figure 4 shows the electro-magnetic field of the prototype spoke cavity, and the cavity parameters are summarized in Table 5 [9]. The target Q_0 for our SSR1 prototyping project is 5×10^9 at E_{acc} = 8 MV/m.

The geometrical beta β_g is slightly different from that in Table 3, because further optimization of the linac design was done after the prototyping project was started. The unit cell length is $\beta_g \lambda / 2$ = 87.0 mm, where λ is the resonant

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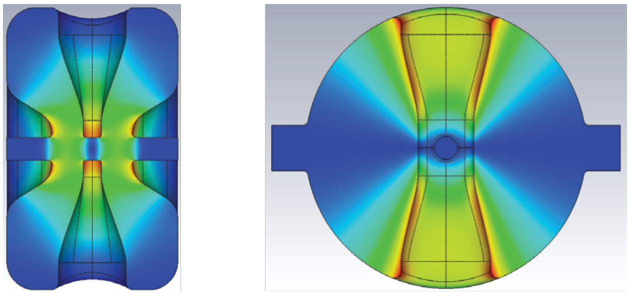

Figure 4: Electric field distribution on y-z plane (left) and magnetic field distribution on x-y plane (right). The z direction is the beam axis.

Table 5: Design Parameters of the prototype spoke cavity

f_0	324 MHz
β_g	0.188
β_{opt}	0.24
Beam aperture	40 mm
Cavity diameter	~ 500 mm
Cavity length	300 mm
L_{eff}	222 mm
G	90 Ω
$T(\beta_{opt})$	0.81
R_{sh}/Q_0	240 Ω
E_{peak}/E_{acc}	4.1
B_{peak}/E_{acc}	7.1 mT/(MV/m)

wavelength. The transit time factor (T) as a function of β is presented in Fig. 5. From this plot, the maximum T is 0.81 at the β_{opt} of 0.24.

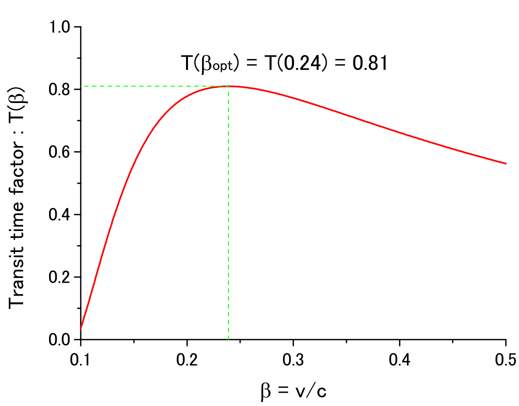

Figure 5: Transit time factor as a function of the beam velocity obtained by the electric field distribution along the beam axis.

The multipacting analysis was also conducted [10], as shown in Fig. 6. The multipacting regions where special care is necessary in processing can be identified from these plots.

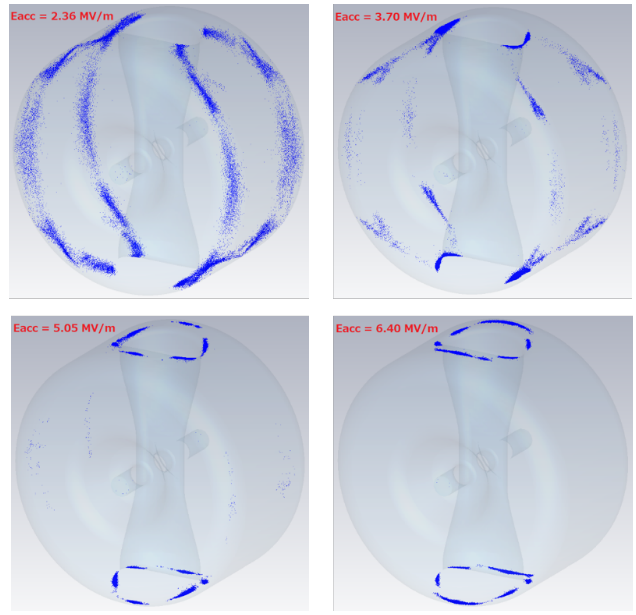

Figure 6: Multipacting analysis using CST. Distributions of multipacting electrons at t = 45 ns with accelerating gradients of E_{acc} = 2.36, 3.70, 5.05, and 6.40 MV/m are plotted.

FABRICATION

The cavity fabrication of the prototype spoke cavity has started in 2020. Figure 7 shows the exploded view of the prototype spoke cavity.

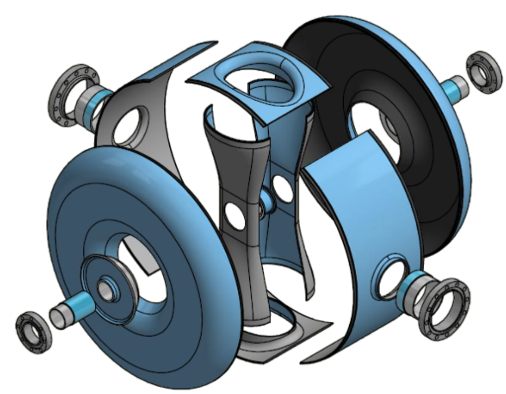

Figure 7: Exploded view of the prototype spoke cavity.

All the materials of our cavity were provided by Tokyo Denkai Co., Ltd. The RRR's of the delivered materials were much more than 300. The main part of the cavity consists of press-formed pure-niobium (Nb) sheets with a thickness of 3.5 mm. Figure 8 shows the press-formed Nb cavity parts.

A drift tube in the spoke electrode and two nose-shaped drift tubes in the end plates were machined from pure niobium ingots. Two RF-ports and two beam-ports flanges were machined from niobium-titanium (Nb-Ti) alloy. The compo-

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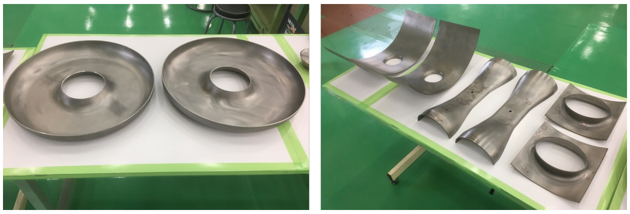

Figure 8: Press-formed parts for the prototype spoke cavity.

sition of the RF-port flange is 55% Nb and 45% Ti. Figure 9 shows the drift tubes and the port flanges.

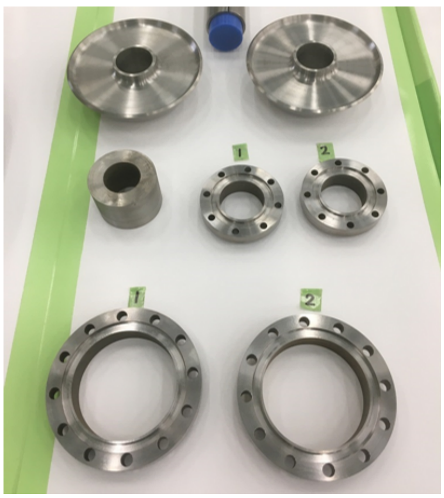

Figure 9: Spoke cavity parts machined from the ingots of pure-Nb or Nb-Ti.

From 2021, the assembly process has been started. All the cavity parts will be joined together by electron beam welding (EBW). Before welding the actual cavity parts, the EBW beam parameters for each welding condition were investigated using Nb test pieces [9]. All the tips to be welded were chemically polished (CP) by a few tens of micrometers with standard a solution composed of HF, HNO_3, and H_3PO_4 to remove contamination prior to EBW. No obvious welding defects, such as unpenetrated welds and welding holes have been found so far. In order to ensure the smoothness of the cavity's inner surface, any notable edges, including the welding-bead undercut, were removed by machine polishing.

CURRENT STATUS

By the end of the Japanese fiscal year 2021, the fabrication of the body assembly has been completed [11]. Figure 10 shows the fabricated body assembly.

In fy2022, beam-port assemblies have been fabricated [12] as shown in Fig. 11.

To confirm the resonant frequency at the current stage, each assembly was temporarily assembled and frequency measurement was conducted [12]. The edges of the body assembly were trimmed by wire cut to eliminate small steps

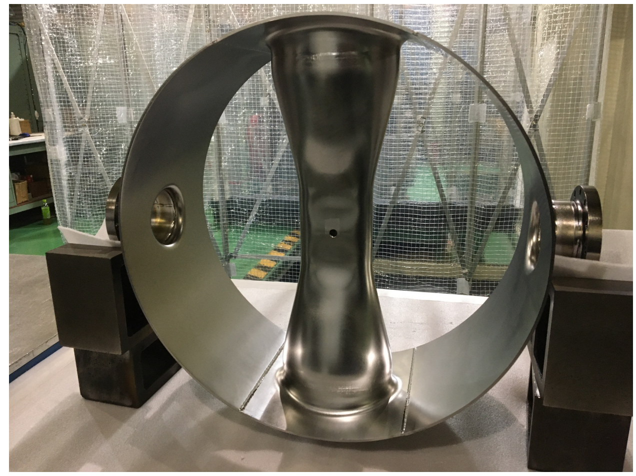

Figure 10: The body assembly of the prototype spoke cavity fabricated in fy2021.

Figure 11: The beam-port assemblies of the prototype spoke cavity fabricated in fy2022. Short pipes for vacuum leak test are attached.

due to the fabrication error. To secure the RF contact between the body assembly and the lid parts, indium wires with a diameter of 1 mm were used. The RF contact between the beam-port assemblies and the lid parts was secured with conductive Aluminum tapes. Straight antennas were inserted into each RF port, and S21 measurement was conducted using a vector network analyzer. Figure 12 shows the measurement setup.

The frequency measured under the atmospheric condition was 332.29 MHz, corresponding to 332.40 MHz in vacuum. The current dimension of the body assembly along the z-direction (beam direction), which is 337 mm, is longer than that of the design value of 300 mm to adjust the frequency at the final EBW process. Figure 13 shows the cavity-length dependence of the f_0 obtained by CST plotted with the measured value. The black squares represent the CST calculation, and the blue square is the calculated valued at the

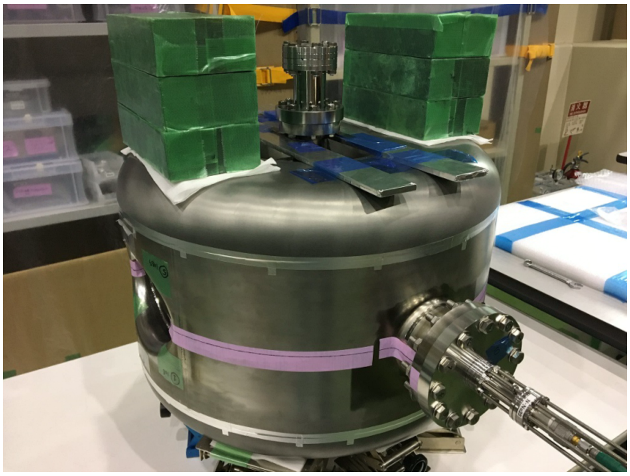

Figure 12: Setup for the frequency measurement.

present cavity length of 337 mm. The red square is the measured value. The frequency difference is 1.07 MHz. This is well within the adjustable range at the final assembly.

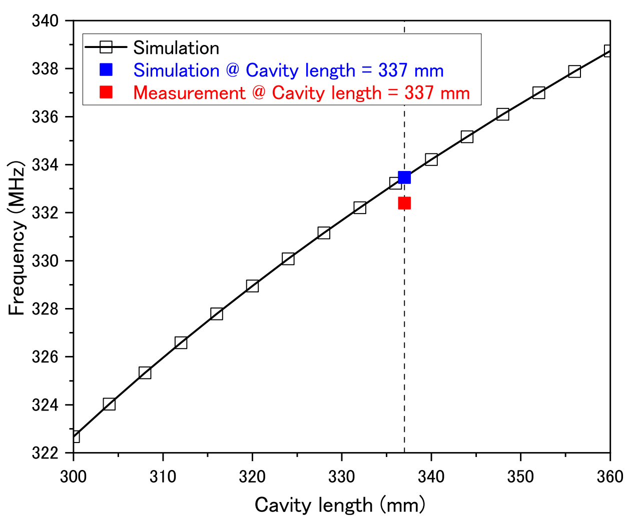

Figure 13: Simulated cavity-length dependence of the fundamental frequency of the prototype spoke cavity. The measured value is also plotted.

SUMMARY

Recently, we restarted the ADS linac development. The low-β section where DTLs were used in the previous NSP design has been changed to using SRF cavities. A fault compensation compatible, fully equipartitioned space-charge dominant linac design has been successfully established. In parallel, spoke cavity prototyping project has been launched. By the end of fy2022, fabrication of the body and beam-ports assemblies has been completed successfully. By measuring the resonant frequency of the temporarily assembled cavity, it was confirmed that there are no significant problems with the cavity fabrication. We will conduct the final assembly and surface treatment such as BCP, HPR, and baking, then perform the vertical test within a few years.

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