

FABRICATION AND RADIO-FREQUENCY TESTS OF A 1.3 GHz 9-CELL COPPER CAVITY AT ROOM TEMPERATURE AS A PROCESS QUALIFICATION STEP FOR NIOBIUM SUPERCONDUCTING CAVITY PRODUCTION

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Abstract

The KU-KEK-KAT collaboration produced a 1.3 GHz copper 9-cell cavity with the goal of establishing a domestic Nb cavity fabrication flow in Korea and performed pre-process verification under the same conditions as the Nb fabrication procedure. Prior to fabrication, the reliability of the actual manufacturing was enhanced through EM simulations and engineering simulations using CST, and the fabricated copper 9-cell cavity was evaluated by measuring the resonance frequency with a network analyser and tuning the frequency using a tuner. For this purpose, we construct new antenna by redesigning and simulating 1-cell measurement antenna to 9-cell antenna for room temperature RF measurement, and all measurements were conducted with this antenna. In the initial measurement after fabrication, the resonance frequency of TM_{010} π -mode was measured to be 1.2978 GHz, and the field flatness was around 34%.

INTRODUCTION

In this study, a 1.3 GHz Tesla-type copper 9-cell cavity was designed [1], fabricated, and experimentally evaluated to support participation in the International Linear Collider (ILC) project [2] and to establish domestic superconducting accelerator fabrication capability. The cavity geometry was based on the superconducting Tesla-type 9-cell structure [3]. Based on the paper design, three copper 9-cell cavities were fabricated at KAT.

The fabricated cavity was evaluated through RF measurements and bead-pull tests to examine key parameters such as resonant frequency, field flatness, and coupling characteristics. The measured results were compared with simulation results and previous studies. The overall design, fabrication, and measurement results are expected to provide an important basis for securing domestic superconducting accelerator fabrication technology and supporting future participation in large-scale international accelerator projects, including the ILC.

ELECTROMAGNETIC SIMULATION

Electromagnetic analysis was carried out by first constructing the cavity using parameters shown in Fig. 1 and Table 1, then performing resonant frequency analysis using the Eigenmode solver. The electric field distribution as shown in Fig. 2 was examined, and the bead size for the bead-pull test was optimized through bead-pull simulations.

Resonance Frequency and E-field Simulation

The electromagnetic (EM) simulation was performed to define the design and evaluate fabrication stability. In particular, the differences between Nb and Cu cavities were compared key parameters (e.g., Q_0 and resonant frequency) of the copper prototype against the reference design.

The electromagnetic design was compared with the superconducting radio frequency (SRF) Tesla-type 9-cell cavity [3]. The target was to keep the error within 0.5% relative to the reference data, while the geometric parameters followed the DESY design.

Table 2 shows the main RF parameters of the 9-cell cavity by EM simulation. The simulation results showed that the resonant frequency difference from the target value was within about 0.1%. In addition, a high R/Q value was maintained, indicating good accelerating efficiency. The shunt impedance and quality factor also satisfied the target values, while the B_p/E_{acc} value showed an error within about 5% of the target.

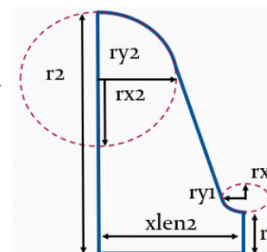


Figure 1: Cavity Parameter Naming.

Table 1: Parameters of 9-Cell Copper Cavity

Parameter	Center-cell [mm]	End-cell 1 [mm]	End-cell 2 [mm]
r1	35.00	39.00	39.00
r2	103.45	103.45	103.45
rx1	9.00	10.00	19.00
rx2	42.00	40.34	42.00
ry1	12.80	13.50	12.00
ry2	42.00	40.34	42.00
xlen2	57.00	56.00	57.7

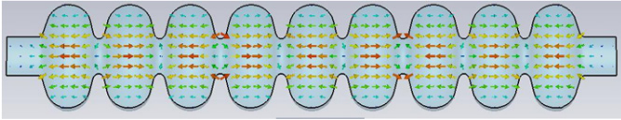


Figure 2: Simulated electric field of TM_{010} π -mode by Eigenmode solver.

Table 2: Main RF Parameters by EM Simulation

Parameter	Value
Frequency	1.299 [GHz]
R/Q	1044.5 [Ohm]
E_p/E_{acc}	2.04
B_p/E_{acc}	4.50 [mT/(MV/m)]
TTF	0.76
Geometrical Factor	267 [Ohm]
Cell-to cell Coupling	2.0 %

Bead-pull Simulation

The bead-pull simulation focuses on defining bead size and step interval to reduce measuring time and improve resolution. The bead path was defined along the cell center, where the electric field is strongest, and the iris center, where the field influence is smallest. Field flatness was evaluated using the ratio of the minimum to maximum electric field, with target values of at least 95 % in simulation and 98 % in measurement [4].

Simulations were conducted for bead diameters of 8 mm and 6 mm. To investigate the effect of the bead step interval, an 8 mm step was applied to the 8 mm bead, while 3 mm, 4 mm, and 6 mm steps were applied to the 6 mm bead.

Figure 3 shows that the electric field distribution on the beam axis calculated using Equation (1) provided the best field flatness performance for the 6 mm bead with a 4 mm step interval, achieving about 99 % field flatness.

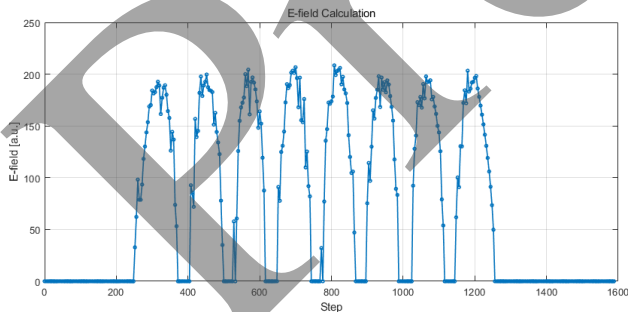


Figure 3: Electric field distribution of 9-cells on the beam axis calculated by Eigenmode solver (1 step = 4.0 mm)

$$E \propto \sqrt{(f_0 - f_m)}. \quad (1)$$

$f_0 =$ Reference Frequency

$f_m =$ Measured Frequency with bead

$$\text{Field Flatness} = \left(\frac{E_{peak,min}}{E_{peak,max}} \right) \times 100\%$$

FABRICATION

The copper 9-cell cavity was fabricated over approximately 8 months, from April 2025 to December 2025. Each cavity was fabricated 58 parts and welded 77 parts by using electron-beam welding (EBW). Appropriate jigs were designed and applied for all welding processes to ensure welding quality. Based on these conditions, three prototypes were fabricated to establish the fabrication technique and process recipe.

The fabrication process consisted of cutting, die forming, machining, and welding, as shown in Fig. 4. Each half-cell was formed by deep drawing. After fabrication, helium leak tests were performed for three cavity prototypes, and all three satisfied the target leak-tightness requirement, as shown in Fig. 5.

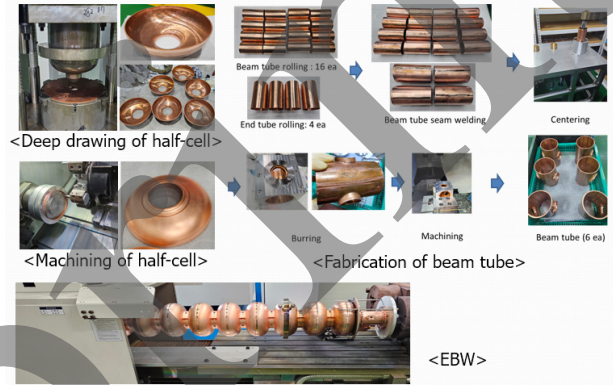


Figure 4: Fabrication Steps for 9-Cell Cavity.

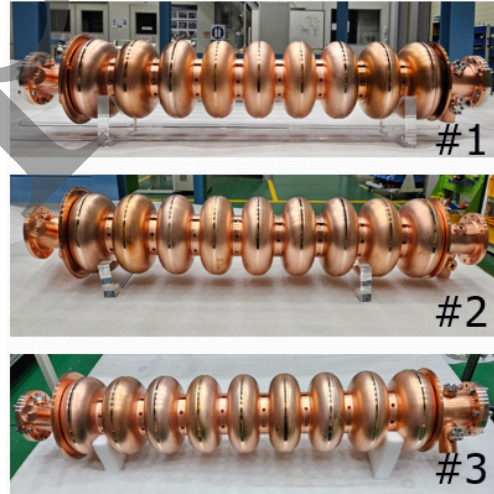


Figure 5: Three Copper Cavities Fabricated by KAT.

MEASUREMENT

Frequency Measurement

RF measurements, shown in Fig. 6, were performed using a Rohde & Schwarz ZNL20 vector network analyser (VNA) to determine the resonant frequency and scattering parameters (S11 and S21). The measured resonant frequencies showed good agreement with the simulation results, validating the electromagnetic design. To establish suitable coupling conditions, one of the three fabricated cavity

prototypes was used for antenna optimization. The antenna insertion depth was adjusted to achieve critical coupling, resulting in $S_{11} \approx -42$ dBm and $S_{21} \approx -33$ dBm, [5]. The optimized antenna lengths were determined to be 123 mm for the input and 52 mm for the output. The results of the RF measurements are shown in Table 3. The obtained coupling configuration provides a stable reference condition for subsequent measurements and will be applied to future characterization of the Nb cavity.

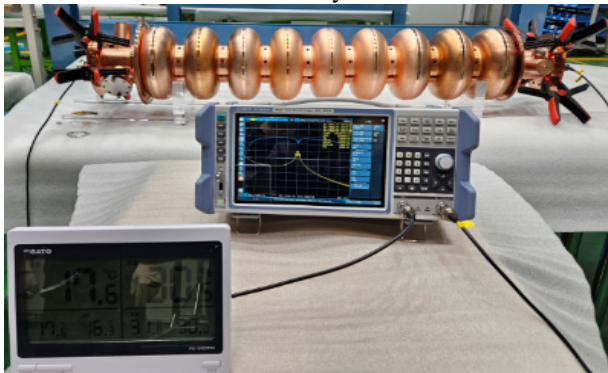


Figure 6: Set-Up of RF Measurement.

Table 3: Result of RF Measurement

Parameter	Value
Frequency (TM ₀₁₀ π -mode)	1.297814 [GHz]
S ₁₁	-42.43 [dBm]
S ₂₁	-32.76 [dBm]
Q _L (Loaded Q)	15488
Q ₀	31110
Q _t (Transmitted Q)	5.874×10^7
Q _{in} (Input Q)	3.086×10^4
Input Coupling Beta	1.008

Bead-pull Test

Based on the simulation results, the bead-pull test was performed using a 6 mm aluminum bead with a 4 mm step interval. Two repeated measurements were conducted to confirm the measurement trend. A resonant frequency shift due to temperature variation was observed; however, fitting results showed that the trend error remained within around 0.5 %.

Since the cavity was in an un-tuned state, the measurement revealed the cell-to-cell electric field distribution and an initial field imbalance. To obtain a preliminary understanding of tuning-induced frequency behavior, each cell was mechanically deformed without a pre-tuning calculation. It was observed that cells #1 – #5 required compression, while cells #6 – #9 required expansion to improve field flatness, as shown in Fig. 7 and Fig. 8.

In future work, the target frequency will be determined through passband mode and cell-to-cell coupling analysis, and tuning will be performed accordingly to achieve the desired frequency and field flatness.

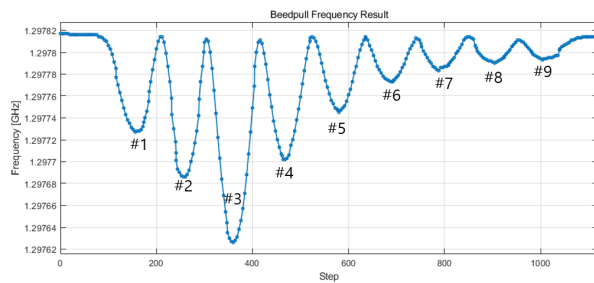


Figure 7: Measured frequency during bead-pull test. (1 step = 4.0 mm)

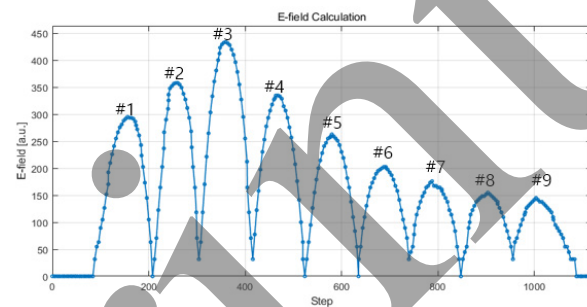


Figure 8: E-field distribution of 9-cell cavity. ($f_0 = 1.297814$ [GHz], Field Flatness = 34%)

CONCLUSION

In this study, 1.3 GHz Tesla-type copper 9-cell cavities were fabricated and measured as a process verification step for future Nb superconducting cavity production. Prior to fabrication, electromagnetic simulations were performed to evaluate the RF characteristics of the copper cavity, including the TM₀₁₀ π -mode frequency, R/Q, Q-related parameters, and electric field distribution. The simulation results showed a TM₀₁₀ π -mode frequency of 1.299 GHz. In addition, bead-pull simulations were used to determine the bead size and step interval, and the expected frequency variation due to tuner deformation was also investigated.

Three copper cavity prototypes were successfully fabricated, and their fabrication quality was confirmed through helium leak tests and RF measurements. In the room temperature RF measurement, the TM₀₁₀ π -mode frequency of the fabricated cavity was measured to be 1.297814 GHz, showing a difference of approximately 0.05% from the simulated result. The measured S-parameters and Q values, including $S_{11} = -42.4$ dBm, $S_{21} = -32.8$ dBm, loaded $Q = 15488$, and $Q_0 = 31110$, also showed good agreement with the expected RF characteristics.

The bead-pull test was performed using a 6 mm aluminum bead with a 4 mm step interval, as determined from the simulation study. By bead-pull test we confirmed the unstable electric field distribution. Based on these results, further cell tuning will be conducted to improve the field flatness and meet the target frequency by calculating cell-to-cell coupling. The fabrication, RF measurement, and bead-pull test procedures established in this study provide a practical basis for future Nb 1.3 GHz 9-cell cavity production and measurement system development.

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