

RF characterization of 1.3 GHz one-cell Nb/Cu full-seamless cavities manufactured by hydroforming

Masashi Yamanaka^{1,*}, Marco Garlaschè², Joanna Sylwia Swieszek,²
 Guillaume Jonathan Rosaz², Hayato Araki¹, Kristof Brunner,² Said Atieh,²
 Carlota P. A. Carlos², Adrià Gallifa Terricabras,² Valentin Giglia², Shinichi Iwamoto,³
 Shinichiro Michizono¹, Yuya Nishi,³ Kazuki Nishimori,³
 Walter Venturini Delsolaro² and Akira Yamamoto¹

¹*High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki, 305-0801 Japan*

²*European Organization for Nuclear Research (CERN), Esplanade des Particules 1,
 1211 Geneva 23, Switzerland*

³*Neuron Japan Co., Ltd., Seika, Kyoto, 619-0237 Japan*



(Received 25 July 2025; accepted 28 January 2026; published 2 March 2026)

In this study, we employ hydroforming technology to develop a 1.3 GHz one-cell Nb/Cu full-seamless cavity to reduce cost and improve performance. Superconducting radiofrequency (SRF) cavities made of pure niobium are expensive because of the material's high cost and the complex manufacturing process, which involves electron beam welding. To overcome these challenges, extensive research has been conducted on using copper substrates coated with niobium, leveraging hydroforming to eliminate welding and seams, thereby reducing cost and simplifying production. The hydroforming process involves expanding oxygen-free copper tubes in two steps, followed by vacuum annealing to recover elongation. This method exhibited high productivity, with forming times of 51 and 78 s for the two steps. However, the process introduced surface roughness, compromising optimal rf performance. Following hydroforming, the cavities were coated with niobium via high-power impulse magnetron sputtering. This coating method ensured excellent film adhesion and can withstand high-pressure water rinsing. We conducted rf measurements of the cavities, achieving an accelerating gradient of 12 MV/m at 4.2 K. The quality factor was slightly below requirements, attributed to surface roughness from the hydroforming process. The maximum accelerating gradient reached 15.7 MV/m at 1.85 K with no field emission. We demonstrate the advantages of full-seamless cavities, including reduced manufacturing costs, high reproducibility, and the elimination of welding seams that can introduce defects. However, challenges such as surface roughness and its impact on the rf performance must still be addressed. This study makes a significant contribution to the development of cost-effective, high-performance SRF cavities for coating studies.

DOI: [10.1103/1jh5-65xh](https://doi.org/10.1103/1jh5-65xh)

I. INTRODUCTION

A superconducting radiofrequency (SRF) accelerator cavity introduces high-power radiofrequency waves into a cell and accelerates the particles by generating an electric field. It is cooled to less than 4 K using liquid helium and can be operated in the superconducting state. Power loss and heat generation are reduced because the electrical resistance is almost zero. Cavities of this type exhibit greater energy efficiency than traditional accelerators;

however, their production incurs high initial costs because of the use of pure niobium (Nb), a rare metal [1].

The fabrication process for an SRF cavity with an elliptical cell typically involves press-forming rolled Nb sheets into a bowl shape, followed by joining them via electron beam welding (EBW). The cavity must have a smooth inner surface, and welding must be performed from outside the cavity because of the typical size of EBW guns. Therefore, good penetration must be achieved during welding to form a smooth penetration bead with minimal protrusion. However, such a challenging welding task requires a high level of expertise. The initial cost of EBW machines is also high, and EBW thus becomes the primary factor that increases the manufacturing cost of SRF cavities.

Extensive research has been conducted on the low-cost fabrication of cavities using hydroforming without

*Contact author: masashi.yamanaka@kek.jp

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EBW [2]. It was first investigated at Cornell University [3]. Singer *et al.* fabricated cavities using an Nb seamless tube with an inner diameter of 150 mm and a wall thickness of 2.7 mm at DESY [4]. The maximum accelerating gradient was 30–35 MV/m. Hydroforming was also used to fabricate three 3-cell cavities, which were then welded together to fabricate a nine-cell cavity. KEK has conducted research on hydroforming since 1994 and has successfully fabricated one- and three-cell cavities from seamless Nb tubes. The maximum accelerating gradient reached 40 MV/m, demonstrating that it can be used as an accelerator cavity [5].

To reduce the cost of SRF cavities, extensive research has been conducted in recent years to manufacture cavity bodies from copper (Cu) and to coat the inner surface with Nb, forming a superconducting layer [6]. At CERN, Nb/Cu cavities were implemented in the Large Electron Positron Collider and later in the Large Hadron Collider [7,8]. They were selected again for the fabrication of quarter-wave resonators (QWR) in the HIE-ISOLDE beam facility [9]. A similar strategy is foreseen as the baseline for some cavities of the Future Circular Collider (FCC) [10]. The main limitation of Nb thin films is the significant increase in surface resistance with increasing rf field amplitude. The Nb/Cu cavity is implemented only for low-accelerating-gradient applications. Calatroni *et al.* reported that the limits of rf performance can be attributed to film defects occasionally observed in the deposited Nb layer, which may arise from the copper substrate itself [8,11]. These defects were observed in the HIE-ISOLDE QWR-coated cavities, where a systematic performance loss was noted in the EB-welded cavities, highlighting the importance of seamless substrates [12]. Palmieri and Vaglio developed a thermal boundary model that explained the decrease in the rf performance based on the quality of the thermal contact at the Nb/Cu interface [13].

The inner surface of the cavity must be as smooth as possible; a seamless cavity is therefore an ideal substrate for coating. By 1989, CERN had successfully manufactured a Cu cavity by hydroforming seamless Cu tubes [14]. They applied an Nb coating and achieved the maximum accelerating gradient of 16 MV/m [15]. CEA Saclay also employed a hydroformed Cu cavity, manufactured by CERN, and applied a Nb coating to achieve a maximum accelerating gradient of 25 MV/m [16].

Another seamless process, which involves the cell being completely spun around a mandrel and then EB-welded to the beam tubes, was investigated at INFN [17,18]. This process was employed to manufacture several 1.3 GHz Cu cavities. However, the high stress involved in the process can cause occasional cracking on the inner surface of the cavity. Removing these damaged surfaces requires complex polishing techniques, making it difficult to determine the final thickness. Moreover, this spinning technique faces challenges in achieving the required mechanical tolerance.

Galvanic processes can be employed as an alternative, seamless approach. In the 1990s, CERN successfully developed Cu cavities through the electrodeposition of Cu on a metalized glass mandrel [19]. A more straightforward etching strategy was employed for Cu electroplating on aluminum mandrels [20]. Better rf measurement results were achieved when compared with other seamless 1.3 GHz Nb/Cu cavities [21,22].

In this study, the authors developed a seamless one-cell Cu cavity using a single seamless tube manufactured via hydroforming to improve performance and reduce manufacturing costs. The target use of this cavity is fundamental coating studies. In 2023, a novel 1.3 GHz one-cell Cu full-seamless hydroformed cavity was successfully prototyped [23], and more than a dozen further tubes were fabricated to demonstrate their high reproducibility [24]. Two Cu cavities, C1 and C1b, were coated with Nb via magnetron sputtering [25] at CERN. Subsequently, the performance of the cavities was evaluated at KEK, yielding satisfactory results. We present the manufacturing processes, surface treatment, Nb thin film coating, and detailed results of the rf measurement. We analyzed the advantages of full-seamless cavities, which are characterized by the absence of seams and welding beads.

II. DESIGN AND MANUFACTURE OF CAVITY

A. Full-seamless cavities

Figure 1 depicts the 1.3 GHz TESLA cell shape considered in this study [26]. A flat section, 1 mm in length, was added to the original design at the equator. The shape accuracy required for the design value is ± 0.4 mm. Figure 2 depicts the components of a one-cell cavity, which include (a) four pieces fabricated using conventional press-forming and welding methods, (b) three pieces, whose cell portion is manufactured via hydroforming and welded to the left and right beam tubes, and (c) one piece without welding beads between both the beam tubes and cell. In previous studies [4,5,14,17], seamless cavities were formed using the technique presented in (b). During this forming process, a tube with a diameter larger than the smallest-diameter part of the cell (called the iris), identical to the beam tube, was employed to facilitate hydroforming.

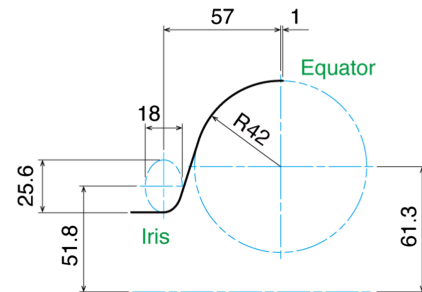


FIG. 1. Cell shape of 1.3-GHz TESLA cavity [24].

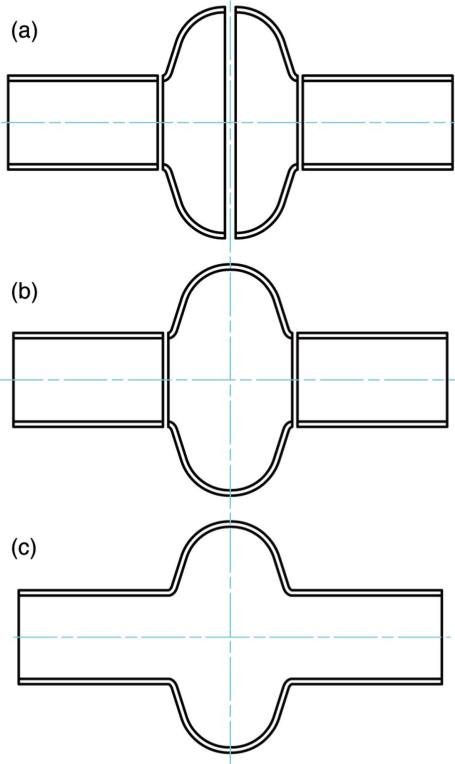


FIG. 2. Components of a one-cell cavity: (a) four pieces made by conventional methods; (b) three pieces whose cell part is manufactured by THF; (c) one piece without welding seams [24].

The iris must be preformed before hydroforming; this process is known as necking [4]. It is similar to spinning and is achieved by using a special profiled roller that moves in both radial and axial directions. The diameter of one portion of the tube is reduced by a necking process. The process time is approximately a few hours for each portion, and the total process time for the necking is quite lengthy. The productivity in (c) without the necking process is higher than that of (b). Therefore, the tube must be cut at the iris and welded after it has been formed. We employed the approach presented in (c), thereby simplifying the process by eliminating welding and necking. We defined the cavities formed using this technique as full-seamless cavities. They are suitable for fabricating a one-cell cavity, but not for a multicell cavity. The cost was evaluated in comparison with the approach presented in (a). The cost of the approach presented in (c) is 28% lower than that of the approach presented in (a) [24]. The Cu electroplated cavity [20] employs the same concept as the approach presented in (c).

B. Properties of copper tube

The initial seamless tube of the 1.3 GHz one-cell full-seamless cavity prototype had an outer diameter of 88 mm, identical to the beam tube diameter, and a wall thickness of 5 mm. Oxygen-free Cu (Japanese Industrial Standard (JIS

C1020) was used as the material. It exhibited a purity of 99.98%, a tensile strength of 219 MPa, an elongation of 67%, and a hardness of 34 HV. High-purity oxygen-free Cu (JIS C1011) was also used for accelerator tubes; however, we used ordinary oxygen-free Cu. Seamless Cu tubes are specified in JIS H3300 [27], and tubes of 4 m length can be obtained from various companies in Japan. The tubes are manufactured via drawing at OKUDA-KINZOKU CO., LTD, Japan. These Cu tubes are commercially available and cost less than 1/65 the cost of Nb tubes.

C. Process of hydroforming

Tube hydroforming is a widely used plastic processing technique. High internal pressure is applied to a tube placed in a die, and both ends of the tube are pushed axially to form the shape of the final product [28]. This technique is widely used in the production of tube fittings and bellows, which have been increasingly implemented in automotive parts in recent years because they can be integrated into hollow, lightweight components, thereby reducing costs [29]. Extensive research has been conducted on hydroforming [30,31].

First, the authors attempted to form a single tube into a cell shape in a single step, which proved to be considerably challenging. Therefore, a two-step forming process was developed, as shown in Fig. 3 [24]. Two types of dies were prepared, and the manufacturing process was completed via hydroforming only. The tube and dies were also arranged vertically owing to the vertical configuration of the hydroforming machine. The bottom of the lower die was fixed, and the upper die was pushed downward. In the first step (HF1), the center of the Cu tube, with an outer diameter of 88 mm, was expanded to approximately 130 mm, and the dies were then replaced. In the second step (HF2), the tube was extended to the final dimensions of approximately 210 mm. Vacuum annealing was performed at 500 °C for

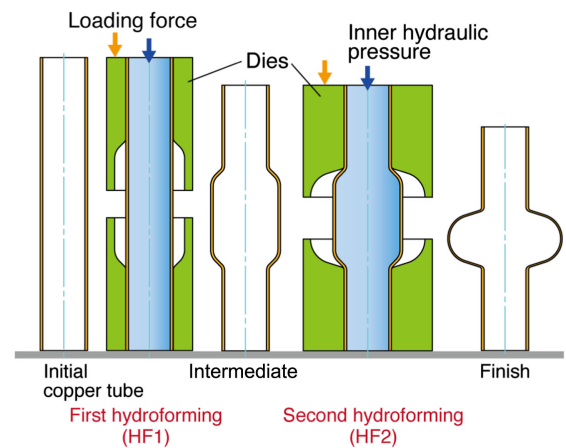


FIG. 3. Two-step forming process for full seamless cavities. Intermediate annealing at 500 °C for 2 h is achieved between HF1 and HF2 [24].

2 h between HF1 and HF2 to recover the elongation. Cu exhibits better formability than Nb. The large diameter section of the cell (called the equator) must be expanded by 2.4 times in circumference when compared with the initial tube. However, no industrial applications have required such a large expansion ratio.

D. Simulations and feasibility using FLD

Finite element method (FEM) simulations were performed using the LS-Dyna software to model the hydro-forming process at CERN. Figure 4 depicts the numerical model used in the simulation for HF1 and HF2. We employed double symmetry and shell elements to enhance the model's efficiency. These simulations enabled the prediction of the material behavior, failure modes, and deformation patterns. The Cu tube was modeled using an elastic-plastic material model with isotropic properties [32]. Process parameters, such as internal pressure and axial displacement (known as the load path), were iteratively optimized to achieve the desired cavity shape while preventing material failure.

To assess the feasibility of the process through FEM simulations, material-specific failure models are required.

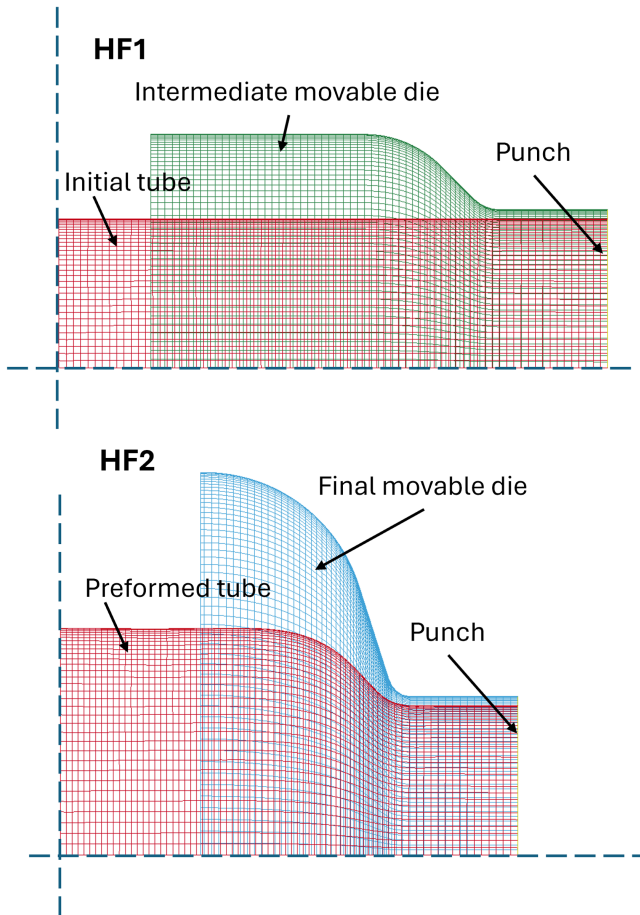


FIG. 4. FEM setup for HF1 and HF2, including symmetry.

Analyzing the in-plane true strains in the forming limit diagram (FLD) is the most effective method for detecting failure in the sheet metal forming process. FLDs for oxygen-free Cu with thicknesses of 2 and 4 mm were obtained by performing tensile tests on two specimen geometries, presenting uniaxial and quasi-plane-strain paths. The FLD exhibits the relationship between minor and major strains, including information on the onset of failure, i.e., the forming limit curve (FLC) [33].

Figure 5 depicts the results of the numerical simulations. The maximum effective plastic strain values were

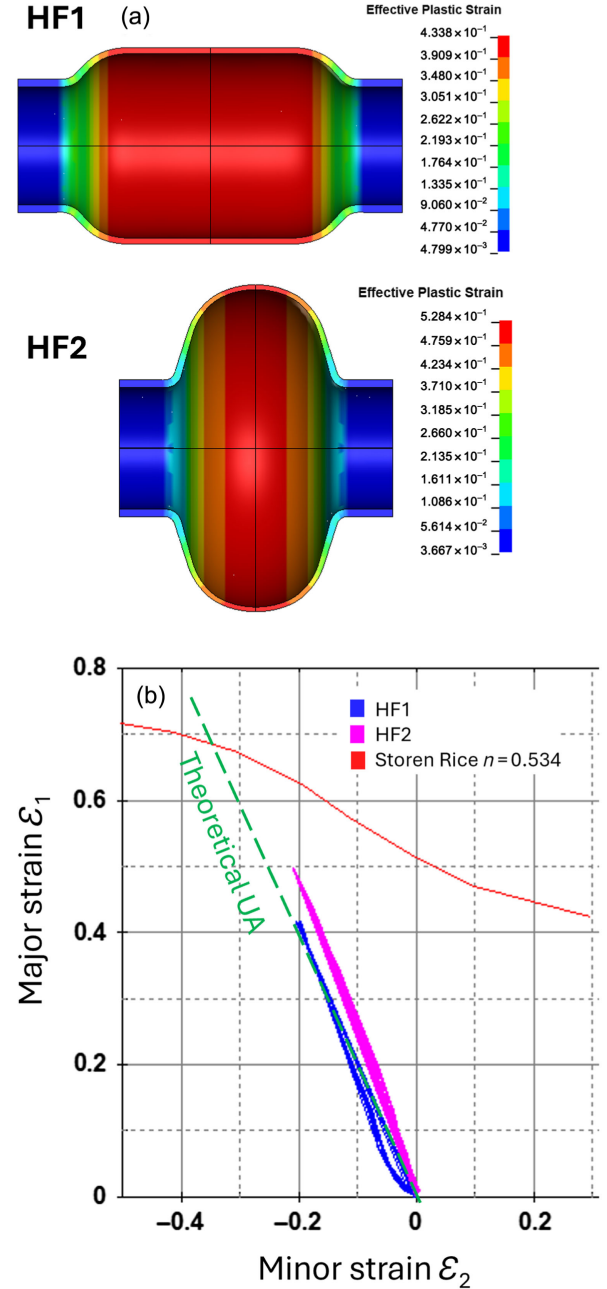


FIG. 5. Result of numerical simulations: (a) distribution of effective strain; (b) forming limit diagram.

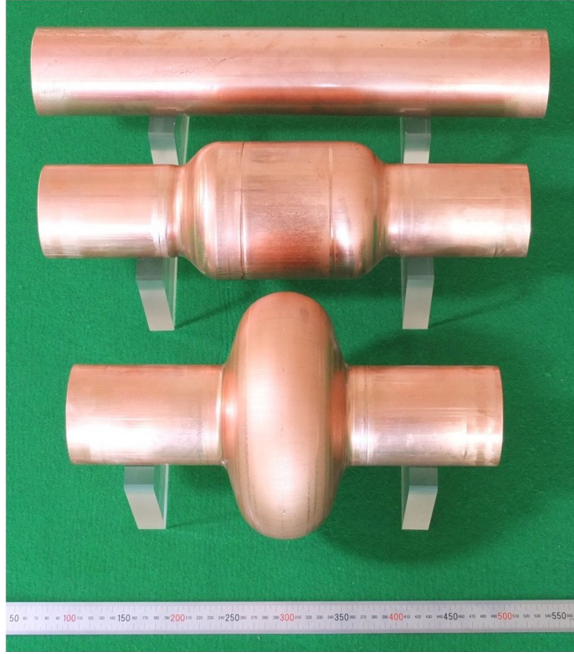


FIG. 6. Formed copper tubes: (upper) initial tube; (middle) after HF1; (lower) after HF2 [24].

approximately 44% for HF1 and 53% for HF2, as shown in (a). In (b), it can be noted how HF1 strain path (blue dots) remains conveniently near to that of a theoretical uniaxial tensile loading condition (dashed-green line); while both HF1 and HF2 were determined to be feasible, as their strain paths remain well below the FLC (solid-red line), defined via Storen Rice theory for copper [33]. At the equator, the minimum thickness after HF2 was simulated to be 2.9 mm, corresponding to a total thinning of 37%. The simulation results indicated that the final cavity shape can be obtained using only two steps. The initial tube length was optimized to balance deformation and material flow. The chosen forming setup induces a uniaxial tension-type deformation, which enhances material formability. The forming process is sensitive to process parameters, wherein applying excessive pressure without compensating for the axial force typically results in plane strain-type or biaxial tension-type

deformations, thereby causing excessive thinning and failure.

E. Manufacture and inspection

Neuron Japan Co., LTD, Japan, performed the specific hydroforming process for the cavities. Figure 6 depicts the formation of the Cu tubes. A hydroforming machine was used to vertically compress the tube, using water as the fluid. The load path can be input as numerical data into the hydroforming machine, and the tube is formed automatically. The forming times for HF1 and HF2 were 51 and 78 s, respectively. The tubes were formed within an extremely short period of time. In the Cu electroplated cavity [20], the electroplating and flange assembly required 90 h, and dissolution of the aluminum mandrel required 1 week. Hydroforming exhibits significant advantages for high productivity.

Table I lists the characteristic values that varied during this process. The thickness of the tubes decreased owing to the forming process, and the central part changed to 3.9 mm after HF1 and 2.6 mm after HF2. The design exhibited a minimum thickness of 2 mm to achieve the required strength. The value after HF2 was 10% smaller than that obtained through the simulation. The tubes that burst in the experiment exhibited significant variations in thickness. In this experiment, the tube was specially manufactured such that the variation in thickness (maximum–minimum value) was less than 0.1 mm. The material expands significantly during the forming process and must be elongated accordingly. However, if the thickness varies significantly, the stress distribution also varies correspondingly; therefore, reducing the thickness distribution is crucial. The hardness increases because of work hardening caused by the forming process and is restored to its initial state through annealing after HF1. Extensive work hardening was observed in HF2 owing to the significant expansion, and the hardness increased even more than in HF1.

Some hydroformed cavities were cut, and the hardness, inner surface roughness, and profile error were measured. The hardness was measured at several points on the cut face along the cell shape after HF1 and HF2, respectively.

TABLE I. Characteristic values that changed during the process. All parameters were measured without destroying tubes [24].

Process	Length (mm)	Outer diameter (mm) [center]	Wall thickness (mm) [center] ^a	Hardness (HV) ^b
Initial	499.6	88	5.02–5.07	34
After HF1	450.1	129.7	3.85–3.92	60
After annealing	...	...	...	26
After HF2	371	216.9	2.6–2.71	84

^aMeasured at every 90° for 4 points by an ultrasonic thickness meter.

^bMeasured using a portable (rebound method) hardness tester. Leeb hardness (HL) is translated to Vickers hardness (HV).

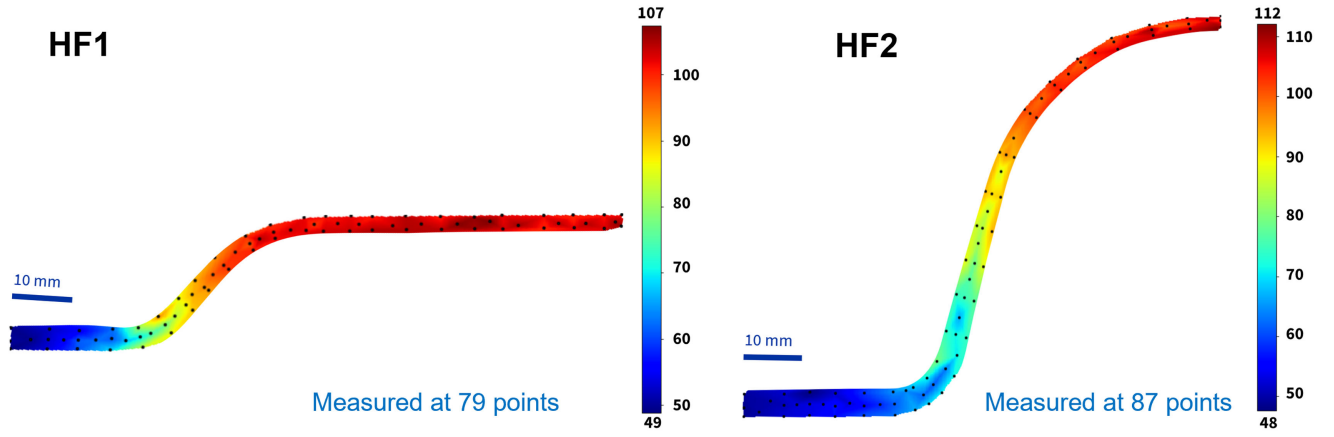


FIG. 7. Measured hardness distribution maps.

Figure 7 depicts the measured hardness distribution maps, wherein the hardness values of the expanded and flat parts after HF1 were almost identical. The initial hardness was 39 HV1, which increased to 107 HV1 during HF1. During HF2, the hardness increased along the cell shape, reaching 121 HV1 at the equator. Figure 8 depicts the inner surface roughness after HF1 and HF2. The average roughness, R_a , was measured at ten positions along the cell shape with an optical profilometer. Multiple profiles were obtained at each point, over an area of $4 \times 2.4 \text{ mm}^2$ along the longitudinal and circumferential directions. The average value was calculated and plotted in the figure. The error bars indicated one standard deviation. The initial roughness, R_a , values were 0.88 and $0.75 \text{ }\mu\text{m}$ along the longitudinal and circumferential directions, respectively. The roughness, R_a , along the longitudinal direction was more significant at all the points. It deteriorated at the equator (position 1) during HF1, reaching approximately $2.8 \text{ }\mu\text{m}$; it further deteriorated during HF2, reaching approximately $3 \text{ }\mu\text{m}$. Following the hydroforming process, the surface appeared rough, commonly referred to as an orange peel. Conversely, the Cu electroplated cavity may exhibit superior surface roughness [20] because of the diamond-turned aluminum mandrel. The surface roughness, R_a , of the Cu sample was $0.03 \text{ }\mu\text{m}$,

but that of the cavity was not measured. The profile error was measured using a coordinate measuring machine. The profile error was 2.2 mm higher at the equator and 3 mm lower at the slope between the equator and the iris. Here, we reused old dies that were manufactured before the simulation. The internal shape of the cell, which was estimated beforehand through simulation from the die shape, exhibited an error of approximately 2 mm from the target value. We conducted an experiment to determine whether the tubes could be formed using the proposed manufacturing process. Furthermore, the profile tolerance of $\pm 0.4 \text{ mm}$ was achieved with new dies that have been recently fabricated.

More than a dozen tubes were successfully fabricated, which demonstrates the high reproducibility of the process. The most essential characteristic, wall thickness after HF2, was statistically analyzed for eight tubes in the same lot. The maximum and minimum thicknesses were 3.02 and 2.42 mm, respectively, with an average of 2.87 mm. The thickness variation for each tube ranged from 0.08 to 0.45 mm, with an average value of 0.23 mm, indicating minimal variation [24]. Following the hydroforming process, both ends of the tube were finished via turning. A mandrel was inserted into the cavity to support it on

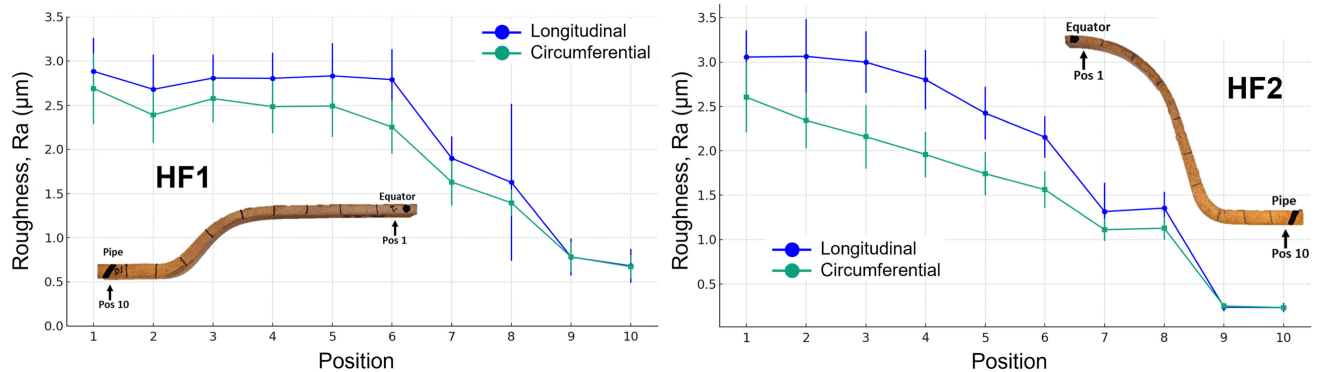


FIG. 8. Measured inner surface roughness profiles.

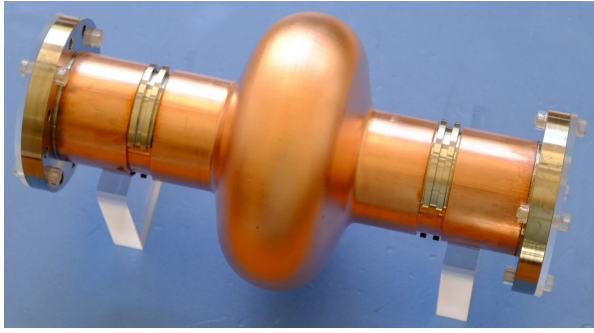


FIG. 9. Finished 1.3 GHz copper one-cell full-seamless cavity with flanges [24].

the turning machine. Flanges, made of stainless steel, were joined to both sides of the tube via EBW, as shown in Fig. 9.

III. SURFACE TREATMENT AND Nb THIN FILM COATING

The two cavities, C1 and C1b, were chemically processed before the Nb deposition. The first step involved degreasing, where the cavities were immersed in an ultrasonic cleaning bath for 3 h at 50 °C to remove residual hydrocarbons and manufacturing-induced contamination. A detergent (NGL 17.40), with a concentration of 20 g/l, was used. Subsequently, the cavities were subjected to

electrolytic polishing in a horizontal position using a mixture of 55% vol. phosphoric acid and 45% vol. butanol, which were maintained at 15 °C and flowed at 10 L/min for 40 min. Electrolytic polishing was applied at a voltage of 12 V and a current density of 75 A/m², resulting in approximately 12 μm of material being removed from the surface. Following electrolytic polishing, the cavities were rinsed with high-pressure water at 100 bars for 1 h. They were then dried by pumping down to 200 mbar for 1.5 h, then to 20 mbar for 1.5 h, and finally to approximately 2×10^{-2} mbar. The cavities were maintained at 50 °C throughout the drying process. They were then cooled to room temperature and backfilled using filtered nitrogen.

The cavities were assembled in an ISO 5 cleanroom onto the coating system [25], as shown in Fig. 10. The cavity (4) was mounted around a cylindrical cathode and insulated from it and the ground using two ceramic vacuum breaks [(2a) and (2b)], respectively. Additionally, two small chambers equipped with a CF-DN16 port were used to connect the anodes. A DN40 port (6) was used on the lower chamber to connect a nonevaporable getter (NEG) pump. At the bottom of the system, an angle valve (5) connects to the ultrahigh vacuum pumping group, which is also equipped with injection valves for the process gas. The cathode assembly comprises a stainless-steel tube (10) with an external diameter of 38 mm, closed at its lower extremity, and welded to the cathode top flange (1); it is highlighted in green in the figure. A central cylindrical

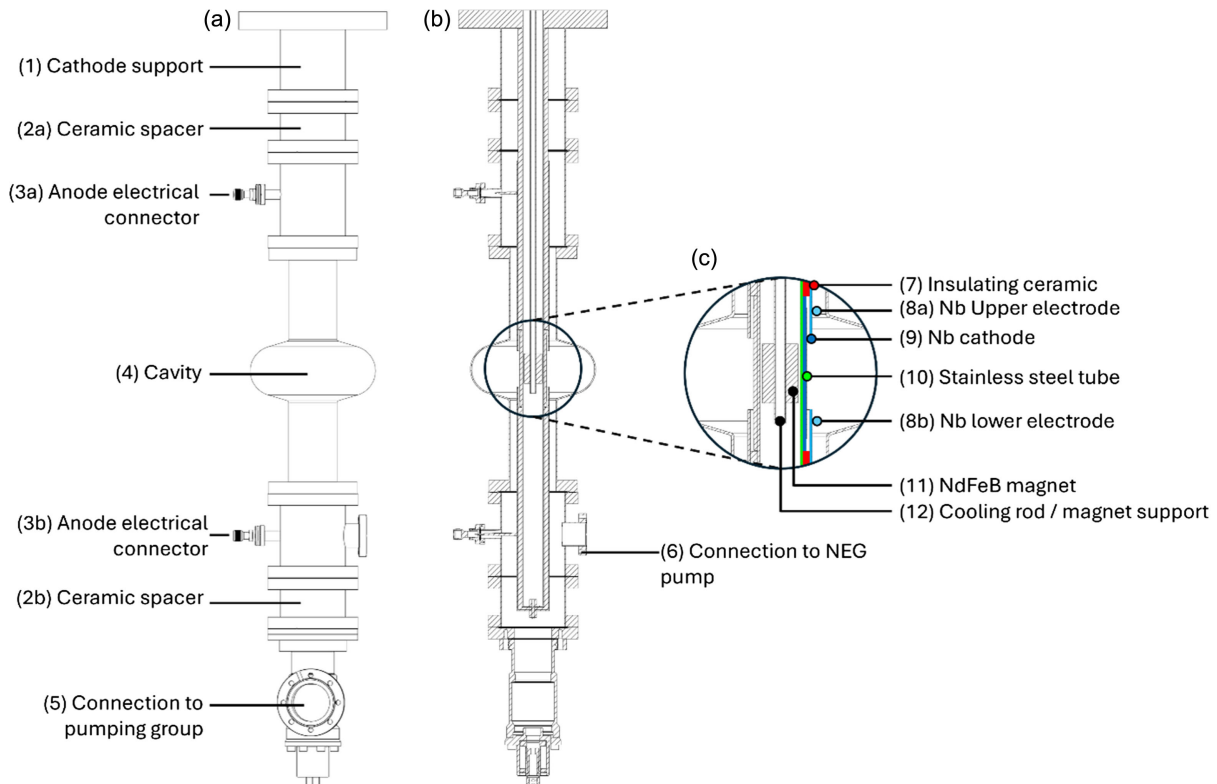


FIG. 10. Coating apparatus for Nb coating; (a) schematic exterior; (b) cross-section view; (c) enlarged view of the cathode assembly.

TABLE II. Coating parameters.

	Beam tube	Cell
Discharge voltage (V)	−480	−650
Discharge peak current (A)	55	220
Average power (W)	350	1200
Frequency (Hz)	200	100
Pulse duration (μs)	100	200
Bias voltage (V)	0 V	−75
Sputtering gas	Kr	Kr
Sputtering pressure (mbar)	0.025	0.0023
Coating temperature (°C)	150	150
Coating duration	10 min	6 h

electrode (9), made of pure Nb with an external diameter of 45 mm, highlighted in dark blue, is placed in direct contact with the stainless steel tube. Two cylindrical Al_2O_3 ceramics (7), highlighted in red, are used as electrical insulators between the central tube and the upper and lower anodes [(8a) and (8b)], respectively, highlighted in light blue. These electrodes with an external diameter of 53 mm are also made of pure Nb. The upper and lower electrodes are electrically connected using type-N UHV connectors [(3a) and (3b)]. Thus, the three electrodes can be independently connected to a power supply or the ground.

The central electrode is connected to the power supply when coating, and the upper and lower electrodes are maintained at ground potential. This indicates that the latter serve as anodes during the plasma discharge, enabling the electron current to flow out of the system and the chamber to be biased at any desired potential. A cylindrical permanent NdFeB (N45SH) magnet (with a length of 50 mm, external diameter of 30 mm, and internal diameter of 10 mm) provides the magnetic field required for sustaining the magnetron discharge. Compressed air in the tube cools the magnet and prevents its demagnetization during the coating process. The system was pumped down

to approximately 1×10^{-7} mbar and baked at 200 °C for 48 h. A nonevaporable pump was activated for 2 h to enhance hydrogen pumping. The pumping group temperature was then reduced to room temperature, and the cavity was actively maintained at 150 °C, reaching a base pressure of approximately 3×10^{-10} mbar.

The coating was performed via high-power impulse magnetron sputtering (HiPIMS), which can be used to produce high-quality SRF films [25,34,35] in two stages. First, the beam tubes were coated using the upper and lower electrodes as the cathodes, with krypton as the discharge gas at a pressure of 2.5×10^{-2} mbar. Six coating steps were used for each beam tube, spaced 25 mm apart by displacing the magnet in the desired positions. The cavities were kept grounded in this step. We used a dc-biased HiPIMS configuration for the cell coating. The cavity was dc-biased, whereas the central cathode was powered with a HiPIMS power supply. Krypton was again used as the 2.3×10^{-3} mbar discharge gas. Table II lists the coating parameters, and Fig. 11 depicts the voltage and current waveforms. The observed waveforms are similar to those obtained when coating cavities that were formed using different forming technologies, demonstrating that the substrate surface does not affect the plasma discharge.

During coating, the cavity was cooled using a fan, maintaining a temperature of 150 °C. Following the coating process, the cavities were heated at 200 °C for 48 h, cooled to room temperature, and then vented using a dry air mixture (80% N_2 and 20% O_2). This coating recipe serves as the baseline for research and development and can therefore be directly compared with those used in previous studies [22]. The cavities were disassembled in the ISO 5 cleanroom, and the high-pressure water rinsing (HPR) at 100 bars for 3 h was performed. Figure 12 presents the optical images of the internal surface of a cavity before and after coating. Despite the shiny finish surface, the electrolytic polishing procedure cannot address the large-scale

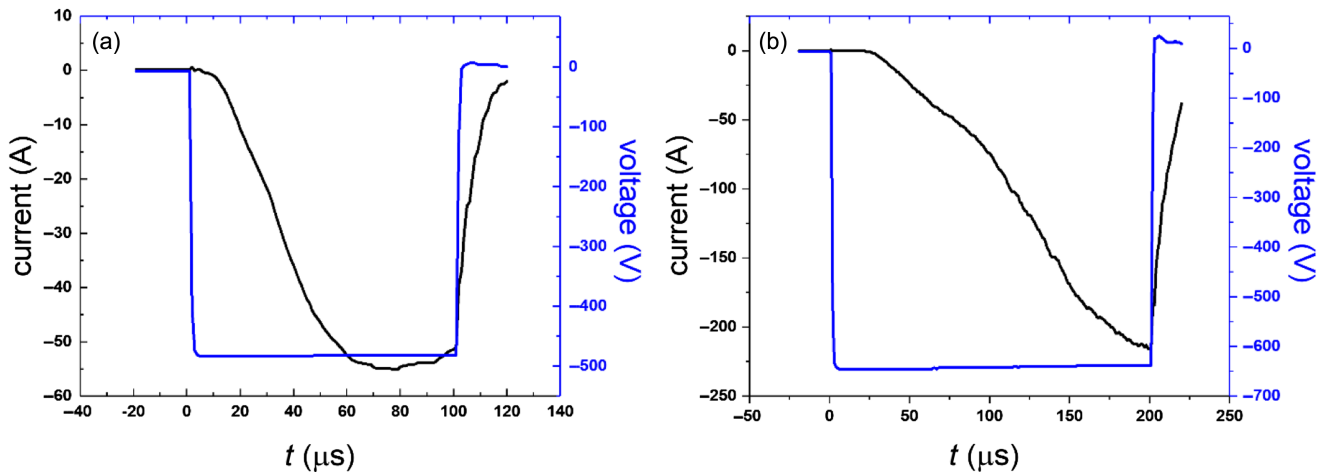


FIG. 11. Typical voltage and current waveforms obtained for plasma discharges in the (a) beam tube and (b) cell of the cavity.

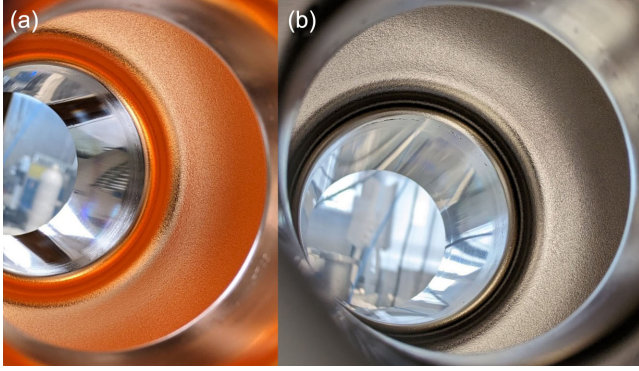


FIG. 12. Optical images of the internal surface of a cavity (a) prior to and (b) after Nb coating.

surface roughness induced by the hydroforming process. However, the film adhesion was excellent and withstood 100 bars of HPR. No foreign particulate could be found in the filter at the outlet of the HPR system, thus validating the film's adhesion.

IV. RF MEASUREMENT

We performed the rf measurements for two cavities, C1 and C1b, at KEK in 2024. We aim to apply hydroforming to Nb/Cu cavities for the FCC-ee project [36]. The quality factor, Q_0 , for the FCC-ee two-cell 400 MHz cavities must be at least 3×10^9 at the nominal accelerating gradient of 12 MV/m [36]. The BCS resistance of an SRF cavity is typically proportional to the square of the rf frequency [1]; therefore, the scaled target performance for a 1.3 GHz cavity is $Q_0 > 4 \times 10^8$ at 12 MV/m [22].

A. Preparation

1. rf parameters

As mentioned above, these cavities exhibited insufficient profile accuracy. The rf parameters were calculated using SUPERFISH [37] with the measured profile, as shown in Table III. The difference between the design and actual parameters was less than 6%. The resonant frequency of one cavity, measured before coating at room temperature using a network analyzer, was 1.270 GHz, which concurs with the calculated value.

TABLE III. rf parameters.

Parameter	Design	Actual	
Resonant frequency f_0 (GHz)	1293.8	1275.4	-1.43%
Characteristic impedance r/Q (Ω)	103.6	102.0	-1.53%
Geometrical factor G (Ω)	280.9	266.6	-5.07%
Surface peak of H H_{sp}/E_{acc}	3392	3566	+5.12%
Surface peak of E E_{sp}/E_{acc}	1.868	1.944	+4.02%

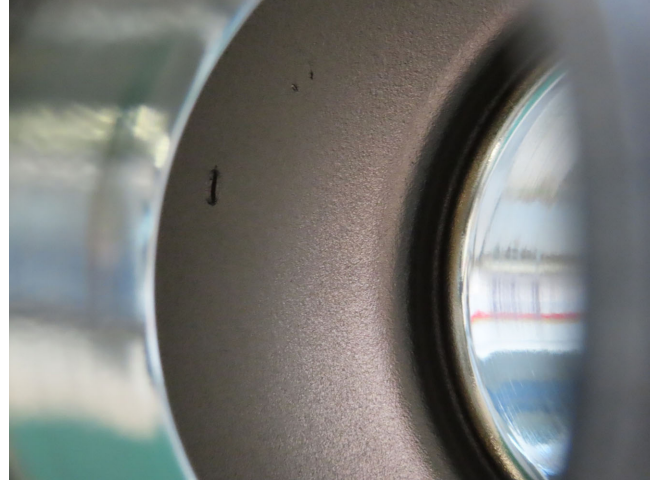


FIG. 13. Dent on the inner surface of C1 cavity. The size is $5 \times 1 \times 0.5$ mm (depth).

2. Procedure before measurement

The rf measurement procedure was based on the standard procedure at KEK-STF [38]. This marks the first instance of measuring the Nb/Cu cavities at KEK, with the preparation procedure established at CERN. The inspection and HPR were performed before measurement. However, the electrolytic polishing and heat treatment for the Nb/Cu cavities after coating were not performed. A dent was observed on the inner surface of C1 during the visual inspection, as shown in Fig. 13. This can be attributed to the mandrel, which was inserted for the machining process after hydroforming and before the coating process, hitting the inner cavity. The inner surface was comprehensively observed using an optical inspection machine [39]. The dent on C1 was located too far from the equator for this camera to capture. Long scratchlike lines were observed on C1b, crossing at right angles to the equator, as shown in Fig. 14. No more defects were found within the field of

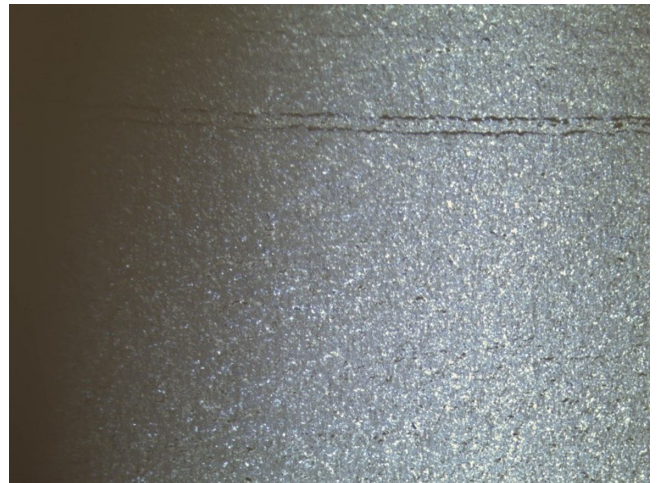


FIG. 14. Scratch line crossing the equator of C1b cavity. The equator is the vertical direction in this picture.

view of the device. HPR was then performed for 6 h, followed by assembly in an ISO Class 4 cleanroom.

B. Q – E curve measurement

The Nb/Cu cavities comprise a bilayer structure; therefore, the thermoelectric current flowing during the superconducting transition increases the residual resistance [12]. This effect can be eliminated by minimizing the temperature gradient during cooldown, which helps optimize the cooling conditions. The temperature gradient is primarily controlled by the mass flow rate of helium and the power of the heater, which is placed at the bottom of the cryostat. The cooling speed was less than 0.1 K/min, and the temperature difference between the cell top and bottom was less than 0.05 K.

Figure 15 depicts the Q – E curves of the C1/C1b cavities. At 4.2 K, both cavities exhibited almost identical behavior. At low gradients below 2 MV/m, the quality factor exceeded 6×10^8 , which is approximately similar to the other measurement results of the 1.3 GHz Nb/Cu cavities [22]. However, the Q -slope was steeper than that of other cavities, and Q_0 was 3×10^8 at 12 MV/m, which was slightly lower than the target value. The measurements were stopped when the target accelerating gradient of 12 MV/m was achieved. No field emission was observed during these measurements.

At 1.85 K, the maximum accelerating gradient of 15.7 MV/m was obtained in C1b. A discontinuous drop in Q_0 was observed while increasing the accelerating gradient in both cavities. However, the cause of this decrease is not apparent. This behavior was not observed in the bulk Nb cavities and can be attributed to Cu substrates or thin films. Both cavities quenched at approximately 16 MV/m without field emission, accompanied by an increase in input power. The quench location of the C1

cavity was identified near the dent, and that of the C1b cavity was near the scratchlike lines, as shown in Fig. 14, based on the temperature mapping. The 1.85 K performance of the Nb/Cu cavities measured at CERN varies significantly [22]. In comparison, these cavities exhibit a relatively high quality factor of over 1×10^{10} in the region up to approximately 5 MV/m. However, the Q -slope was much higher after the Q -drop than in the other cavities, and Q_0 decreased to approximately 1×10^9 at 15 MV/m. A comparison of these results is notable; however, the differences between the facilities and measurement methods must be considered. We aim to remeasure the same two cavities at CERN, thereby evaluating the difference and subsequently comparing the cavity performance.

The surface resistance, R_s , of a superconducting cavity can be decomposed into a temperature-dependent component (BCS resistance, R_{BCS}) and a temperature-independent component (residual resistance, R_{res}) [1]. In KEK, the quality factors are measured at each gradient and each temperature from 2.0 K to approximately 1.4 K, and they are fitted as follows:

$$R_s(T) = \frac{p_0}{T} \exp\left(-\frac{p_1}{T}\right) + R_{\text{res}}, \quad (1)$$

where p_0 , p_1 , and R_{res} denote the fitting parameters [40]. The BCS resistance, R_{BCS} , is the first term on the right-hand side of the equation. Figure 16 depicts the acceleration gradient dependence of the BCS resistance and residual resistance up to 6 MV/m of the C1b cavity. The minimum residual resistance was 2.6 nΩ at 1.0 MV/m. This residual resistance is smaller than that of a similar Nb/Cu cavity [22] and close to that of a Nb bulk cavity without the high- Q recipe.

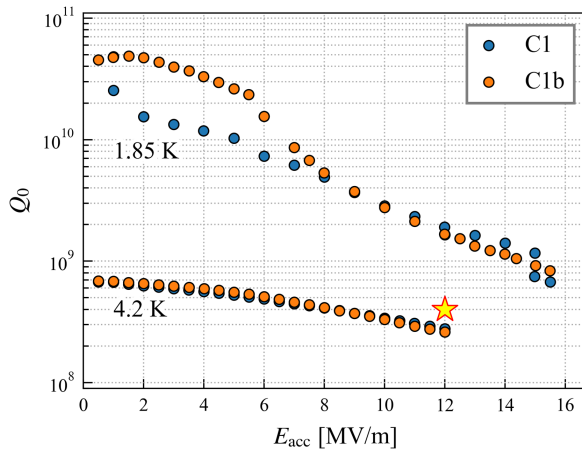


FIG. 15. Quality factor (Q_0) vs accelerating gradient (E_{acc}) measurement result at 4.2 and 1.85 K. The target performance ($Q_0 = 4 \times 10^8$ at 12 MV/m at 4 K) is shown as a yellow star.

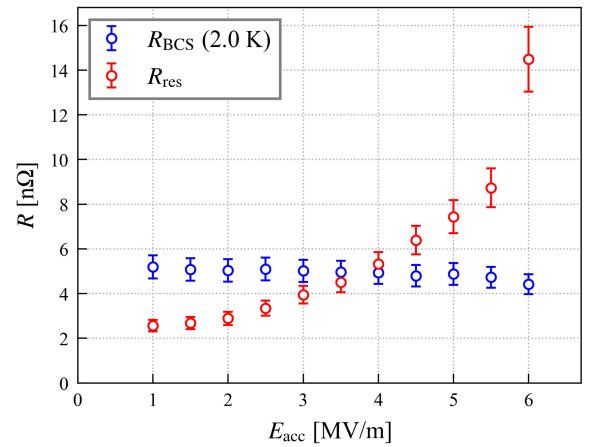


FIG. 16. Deconvoluted surface resistance of C1b cavity into BCS resistance and residual resistance at each accelerating gradient.

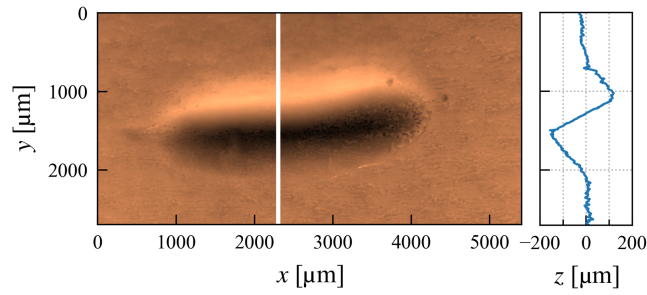


FIG. 17. Profiles of the dent on C1 cavity observed with a laser microscope.

C. After cold measurements

The inner surface of the cavity was observed visually and with the optical inspection machine after the measurement to ensure that there were no changes from before the measurement. A replica of C1 dent and its surroundings were observed with a laser microscope. Figure 17 depicts the result. The area surrounding the dent exhibited a height difference of approximately $+100/-150$ μm . The surface roughness, R_a , in the remaining area was 2.1 ± 0.8 μm . This value is one order of magnitude larger than the typical electrolytically polished bulk Nb cavities and contributes to a higher-than-expected surface resistance. It is assumed that an ideal Nb layer may not be formed using standard coating recipes on a rough surface because of the hydroforming process.

D. Merits of full-seamless cavities

The field emission was not generated in either cavity at 4.2 or 1.85 K, respectively. The two $Q - E$ curves at 4.2 K depicted in Fig. 15 nearly overlap. The rf performance of the full-seamless cavity at 4.2 K is reproducible within a reasonable range at low field. The results highlight the advantages of full-seamless cavities. We only evaluated two cavities in this study, and we aim to evaluate more cavities to verify the merits of full-seamless cavities.

V. CONCLUSIONS

In this study, we fabricated 1.3 GHz one-cell Cu full-seamless cavities. Two cavities were coated with Nb via magnetron sputtering, and the cavity performance was evaluated. We validated the manufacturing process for the one-cell Nb/Cu full-seamless cavities. The main findings of this study can be summarized as follows: (1) We developed a manufacturing process for a full-seamless cavity via hydroforming and simulated the forming conditions, demonstrating the feasibility of the forming process. (2) We successfully fabricated more than a dozen cavities. The forming times for the two steps were 51 and 78 s, respectively, and the cavity was formed exceptionally quickly. This high productivity is superior to the alternative electroplating process. However, the roughness of the

finished surface presents various disadvantages. (3) Nb coating was applied onto the cavities after being electrolytically polished at CERN using the dc-biased HiPIMS technology. The latter exhibited limited capability in reducing the surface roughness; however, the film adhesion was excellent and could withstand a water rinsing of 100 bars. (4) The rf performance of the two cavities was measured at KEK. Both cavities achieved an accelerating gradient higher than the target of 12 MV/m. However, the quality factor at 4.2 K was slightly below the target FCC requirement. The maximum accelerating gradient of 15.7 MV/m was obtained at 1.85 K. (5) Challenges such as the surface roughness and its impact on the rf performance must still be addressed. Future work should focus on optimizing the manufacturing process, enhancing surface treatment, and demonstrating the benefits of full-seamless cavities.

ACKNOWLEDGMENTS

A grant from the Amada Foundation in Japan supported this work. KEK Mechanical Engineering Center and Innovation Center for Applied Superconducting Accelerators also supported this study. We express our sincere gratitude to them.

DATA AVAILABILITY

The data are not publicly available. The data are available from the authors upon reasonable request.

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