LOW TEMPERATURE PROPERTIES OF 20 K COOLED TEST CAVITY FOR C-BAND 2.6-CELL PHOTOCATHODE RF GUN*

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Abstract

In order to examine the basic properties of a cryogenic C-band photocathode RF gun cavity, a 2.6-cell π-mode test cavity was fabricated in KEK. The temperature dependence of the resonant frequency and the Q-value in the cavity were measured ranging from room temperature to 21 K. The increase in the resonant frequency by the cavity cooling from 296.65 K to 21 K has been 188 kHz greater than the one estimated from the linear expansion coefficients for OFHC copper material. The unloaded Q-value of 64650 at 21 K has been in agreement with the result of the SUPERFISH calculation carried out by assuming the surface resistance of the copper material to be 3.54×10^{-3} Ω at 5712 MHz on the basis of the theory of the anomalous skin effect.

INTRODUCTION

A cryogenic C-band 2.6-cell photocathode RF gun, which operates at 20 K, is under development at Nihon University for the future possibility of use in a compact linac-driven X-ray source at KEK [1]. The cavity material is 6N8 high purity copper with the residual resistance ratio (RRR) higher than 3000, which is considered effective to suppress the RF power loss in the cavity wall significantly at low temperatures. The operating frequency of the RF gun cavity is 5712 MHz. The main specifications of the gun are listed in Table 1 [2]. In order to investigate the low-temperature properties of the cavity, a 2.6-cell π-mode test cavity was fabricated in KEK with ultra-precision machining and diffusion bonding techniques. Since it was intended to examine the effect of the high purity copper material on the low-power RF properties at 20 K, the cavity consisted of only axis-symmetric components as shown in Fig. 1 [2]. Thus, the two-dimensional code POISSON-SUPERFISH [3] was used for the design calculation of the cavity.

In the measurements at room temperature, the resonant frequency converted to 23.5 °C in vacuum was approximately 300 kHz lower than the designed value. The unloaded Q-value and the shunt impedance deduced from the field distribution measurement have shown good agreement with the SUPERFISH simulation [2,4].

In this paper the RF properties of the cavity measured at around 20 K are reported and compared with the predicted values from the SUPERFISH simulation and the NIST data for the linear expansion coefficients of OFHC copper [5].

Table 1: Specifications for the 2.6-Cell 20 K Cryogenic Photocathode RF Gun [2]

RF frequency	5712	MHz
Source peak RF power	4	MW
Q_0	> 60000 @20 K > 11000 @298 K	
Shunt impedance	~ 550 @20 K ~ 100 @298 K	MΩ/m
Coupling coefficient	20	
Cavity length	68.2	mm
RF pulse duration	2	μs
RF pulse repetition rate	50	Hz
Maximum wall RF loss	0.73	MW
Output beam energy	3	MeV
RF duty factor	0.01	%
Maximum beam charge	0.5	nC/bunch
Laser pulse repetition rate	357	MHz
Laser pulse length	10-20	ps
Maximum beam energy	3.5	MeV

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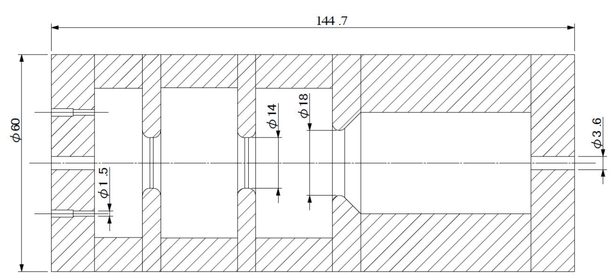

Figure 1: Cross-sectional view of the test cavity. The RF power is fed into the cavity through an antenna inserted into either hole in the left-side end plate.

EXPERIMENTAL SETUP

The experiment has been carried out using a cryogenic cooling system in KEK. The cooling system consists of a cylindrical vacuum chamber and a refrigerator unit (Daikin Industries V108C5L) installed on the top of the chamber. The test cavity has been mounted on a copper base plate with a cylindrical surface having the same radius as the outer side wall of the cavity. The base plate has been attached to the cold head of the refrigerator through a copper fitting plate and a copper block as shown in Fig. 2. Silicon thermal grease has been applied to both sides of the base plate to improve the thermal conductance between the cavity and the fitting plate. The cavity temperature has been monitored by semiconductor temperature sensors

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attached to both the plane surfaces of the end plates of the cavity.

The RF power from a network analyzer (Agilent Technologies E5071C) has been fed into the cavity through an antenna inserted into the center hole of the left-side end plate in Fig. 1. The stripped inner conductor of a semi-rigid cable has been used as the antenna, the outer shield being contacted with the end plate to suppress electric noises. The insertion length of the antenna has been short enough not to affect the cavity resonant frequency, which has been adjusted from the outside of the chamber through a linear motion feedthrough. The π-mode resonant frequency has been traced and saved automatically to a PC every 5 sec during the cooling process together with the cavity temperature and the $|S_{11}|$ values around the resonance peak.

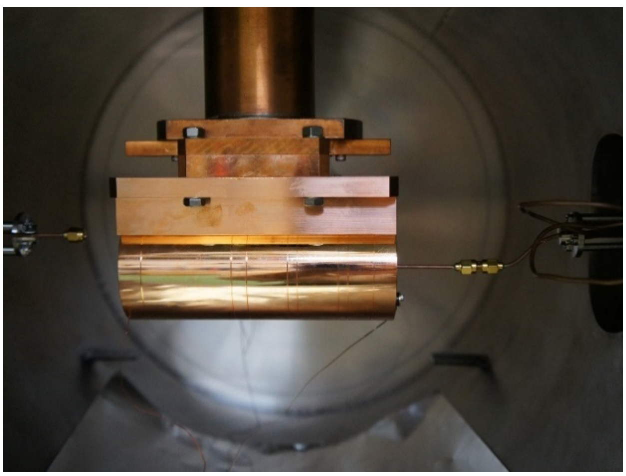

Figure 2: Setup of the test cavity in the cryogenic cooling system. The RF power is fed into the cavity through the antenna inserted into the center hole of the right-side end plate in this picture.

TEMPERATURE DEPENDENCE OF THE RESONANT FREQUENCY

Change in the cavity temperature and the π-mode resonant frequency measured in the experiment are shown in Fig. 3 as a function of the time elapsed since the refrigerator was switched on. It took approximately 2.5 hours to cool the cavity down to nearly 22 K. The resonant frequency measured at the beginning of the experiment was approximately 5692.67 kHz at 23.5 °C in vacuum, which is 300 kHz lower than the design frequency that was expected from the cavity dimensions specified for machining at 23.5 °C. At the lowest cavity temperature of 21.27 K in the experiment, the resonant frequency was 5711.76 MHz.

The dependence of the resonant frequency on the cavity temperature is shown in Fig. 4, where the experimental result is compared with the calculation based on the linear expansion coefficients of OFHC copper from NIST [5]. The calculated values have been normalized to the experimental value at 23.5 °C. The experimental frequency obtained at 21.27 K has been 188 kHz higher than the calculated one. In the region from 30 K to 21.27 K, the experimental result has shown the frequency change of approximately 30 kHz, which is 1/27 of that for the same temperature difference in the room temperature region.

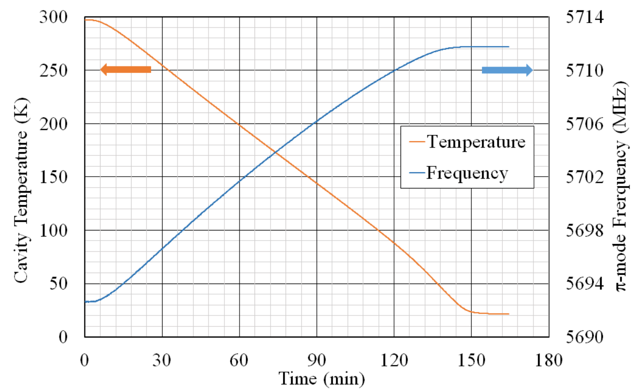

Figure 3: The cavity temperature and the π-mode frequency as a function of the time elapsed since the refrigerator was switched on.

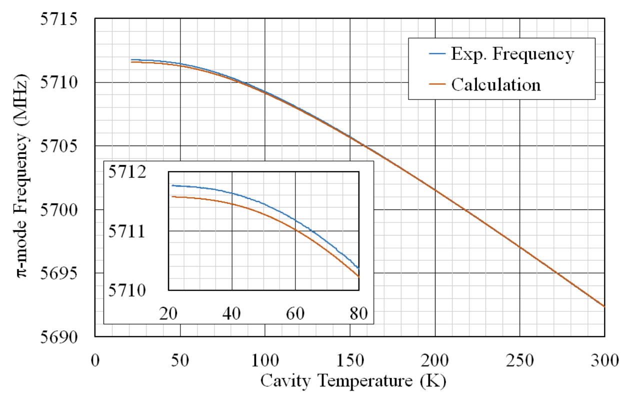

Figure 4: Comparison of temperature dependence of the resonant frequency between the experimental result and the calculated result based on the linear expansion coefficients of OFHC copper from NIST [5].

TEMPERATURE DEPENCENCE OF THE Q-VALUE

Change in the Q-value of the cavity during the process of cooling from room temperature to 21.27 K was monitored graphically by observing the behavior of $|S_{11}|$ on the display of the network analyzer. The plots of $|S_{11}|$ at room temperature and at the lowest temperature are shown in Fig. 5 and 6. The loaded Q-value at each temperature

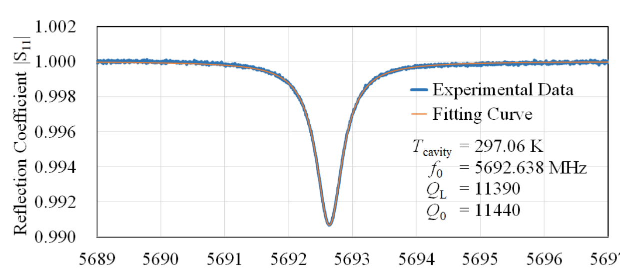

Figure 5: Plot of $|S_{11}|$ around the π-mode resonance peak at room temperature.

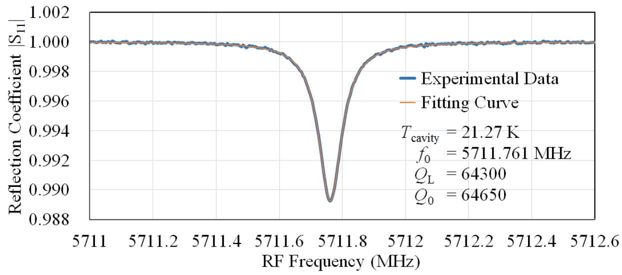

Figure 6: Plot of $|S_{11}|$ of the -mode resonance at the lowest temperature in the experiment.

was deduced from the parameters for the RF resonant absorption curve that was fitted to the $|S_{11}|$ plot, and then it was converted to the unloaded Q-value using the $|S_{11}|$ at the minimum reflection. The difference between the loaded and the unloaded Q-values has been very small, since the coupling coefficient between the antenna and the cavity was kept small in the experiment.

The behavior of the unloaded Q-value, evaluated at approximately every 10 K, is shown in Fig. 7 as a function of the cavity temperature. The experimental results are indicated by closed red circles. In the temperature region lower than 100 K, the Q-value has shown a significant increase.

The solid curve in Fig. 7 shows the behavior of the Q-value predicted from the temperature dependent surface resistance of the cavity. The surface resistances at 5712 MHz for RRR=3000 copper have been calculated in the temperature range from 300 to 20 K by the theory of the anomalous skin effect [6]. The Q-value $Q(T)$ at temperature T is inversely proportional to the surface resistance $R_s(T)$. Thus, $Q(T)$ has been deduced from the relation $Q(T) = Q(T_0)R_s(T_0)/R_s(T)$, where $Q(T_0)$ at the reference temperature T_0 has been obtained from the SUPERFISH calculation using the surface resistance $R_s(T_0)$. The dependence of the Q-value on the cavity temperature is in agreement with the experimental result. In the temperature region lower than 50 K, the experimental values tend to be higher than the predicted ones from the anomalous skin effect.

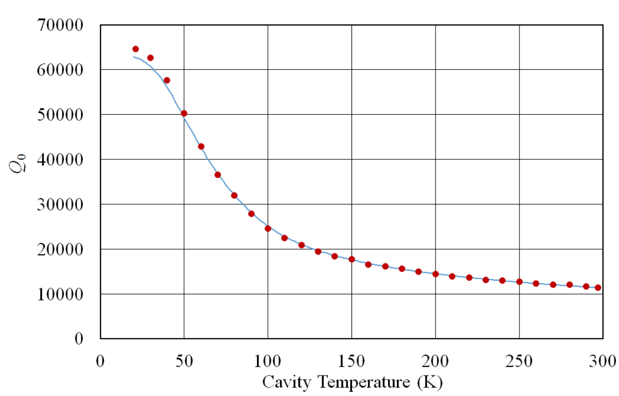

Figure 7: Plot of the unloaded Q-values obtained from the $|S_{11}|$ data accumulated in the cooling experiment. The solid curve shows the predicted values based on the anomalous skin effect.

Table 2 lists the results of the π-mode resonant frequencies and the Q-values obtained by the experiment and the calculation, respectively. The maximum Q-value of 64650 obtained at 21.27 K is 5.65 times as high as that at 296.65 K, which is 2.8 % higher than the result of calculation based on the anomalous skin effect.

Table 2: The π-mode Resonant Frequencies and the Unloaded Q-values Obtained from the Experiment and the Calculation

	Experiment		Calculation	
Temperature (K)	296.65	21.27	296.65	21.27
Frequency (MHz)	5692.67	5711.76	5692.97	5711.57*
Unloaded Q-value	11465	64650	11400	62900

* Estimation based on the experimental frequency at 296.65 K.

CONCLUSION

The low temperature RF properties of the C-band 2.6-cell basic test cavity for a 20 K cryogenic photocathode RF gun has been investigated by the collaboration between KEK and Nihon University as part of Photon and Quantum Basic Research Coordinated Development Program of the Japanese Ministry of Education, Culture, Sports, Science, and Technology (MEXT). The π-mode resonant frequency has increased from 5692.67 MHz to 5711.76 MHz by the cooling of the cavity from 296.65 K to 21.27 K, the increase being 188 kHz greater than the calculation using the linear expansion coefficients from NIST. On the other hand, the unloaded Q-value at 21.27 K has been 5.65 times as high as that at room temperature, which is fairly in agreement with which was predicted by the theory of the anomalous skin effect. Based on the present result a new cavity equipped with an RF input coupler has been designed and in preparation for tests in the next stage [7].

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