RF CHARACTERISTICS OF 20K CRYOGENIC 2.6-CELL PHOTOCATHODE RF-GUN TEST CAVITY*

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Abstract

A cryogenic C-band photocathode RF-gun operating at 20 K is under development at LEBRA in Nihon University. The RF-gun is of the BNL-type 2.6-cell pillbox cavity with the resonant frequency of 5712 MHz. The 6N8 high purity OFHC copper (corresponding to RRR-3000) is used as the cavity material. From the theoretical evaluation of the anomalous skin effect, the quality factor Q of the cavity at the operating temperature of 20 K has been expected to be approximately 60000. The cavity basic design and the beam bunching simulation were carried out using Poisson Superfish and General Particle Tracer (GPT). Machining and diffusion bonding of the RF-gun cavity was carried out in KEK. After diffusion bonding the Q_0 value of the π-mode resonance at the room temperature (23.5 °C) was approximately 11440.

INTRODUCTION

A C-band photocathode RF gun is under development for future use in the compact accelerator developed at KEK [1] as a high brightness X-ray source. As a basic design the RF gun cavity consists of 2.6-cell pillbox-type π-mode structure and operates at 5712 MHz under low temperature of 20 K. The electron beam is extracted by using a cryogenically-cooled copper RF cavity, which can be driven with considerably low RF power compared to those in room temperature RF guns. A low power test cavity has been designed with Poisson Superfish [2] for basic understanding of the RF properties at low temperature. The simulation of the beam bunching was performed using General Particle Tracer (GPT) [3]. This paper reports the results of the beam simulation and the low power RF properties measured at room temperature.

LOW-TEMPERATURE PROPERTIES FOR HIGH PURITY OXYGEN FREE COPPER

The dimensional variation ratio of higher purity oxygen free copper (OFHC copper (UNS C10100/C10200)) was obtained from the linear expansion coefficient data in the database of National Institute of Standards and Technology (NIST) (temperature range from 4 to 300 K) [4]. The deduced dimensional change in the cavity between room temperature and 20 K is 0.33428%. In addition, the linear expansion coefficient at around 20 K is around 1/100 of that in the room temperature. This means that the temperature dependence of the cavity resonant frequency is very low. The temperature dependence of the thermal conductivities in different OFHC copper Residual Resistivity Ratios (RRR) were also obtained from the NIST database, which is shown in Fig. 1 for the OFHC copper material of RRR-50 to 500. Fig. 1 suggests that the thermal conductivity at around 20 K is expected to be more than 10 times larger compared with that in room temperature by using a high purity OFHC copper exceeding RRR-500. Therefore, an RF gun cavity made of high purity OFHC copper has a possibility of stable pulsed operation at around 20 K.

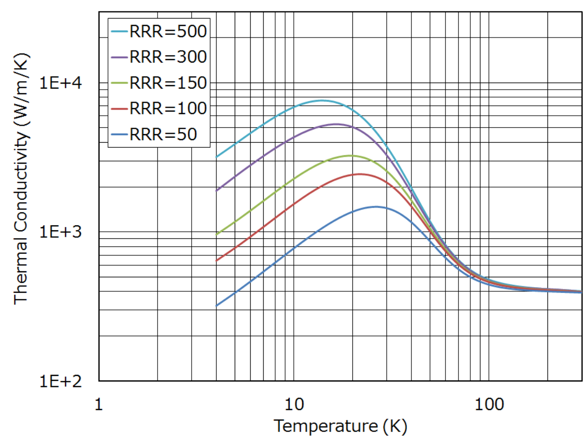

Figure 1: Thermal conductivity of coppers with different residual resistivity ratio (RRR-50 to 500)

CAVITY CHARACTERISTICS

The surface resistance of the RF cavity is an important parameter which determines the wall RF loss and the Q value, and is dominated by the skin depth in room temperature domain. However, the electron mean free path in material is extremely long compared to the skin depth in low temperature region, which causes a higher surface resistance than that is predicted by the skin depth. This behavior is known as the anomalous skin effect. The behavior of the surface resistance at 5712 MHz was calculated on the basis of the Reuter's theory of the anomalous skin effect [5], which is shown in Fig. 2 together with the result of calculation of the normal skin effect for comparison. As seen in Fig. 2, the surface resistance of the cavity at 20 K is reduced to

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approximately 18% of that at room temperature, which means that the quality factor of the cavity is 5.5 times as large as that at room temperature. The Q value of the cavity resulted from the Superfish calculation is approximately 11000, which corresponds to approximately 60000 at 20 K.

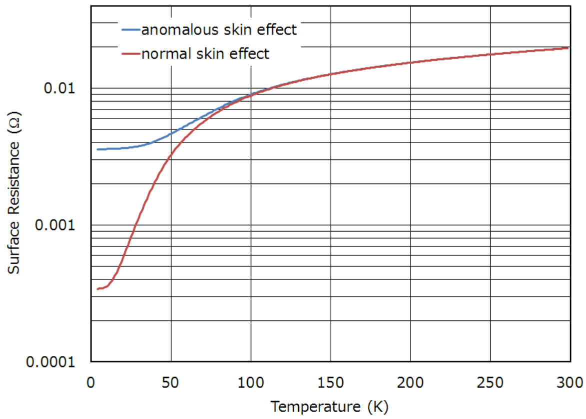

Figure 2: Temperature dependence of theoretical surface resistances of RRR = 3000 copper at 5712 MHz. Blue line: result of the anomalous skin effect, Red line: the normal skin effect.

SPECIFICATIONS OF THE 2.6 CELL RF GUN

The RF gun consists of a BNL-type 2.6-cell π-mode cavity with the resonant frequency of 5712 MHz under low temperature of 20 K. Cooling of the cavity is performed by two cryogenic coolers with total cooling capacity of 100 W. The design specifications for the cryogenic cooling copper RF gun cavity has been determined as listed in Table 1. A low power test cavity has been designed with Poisson Superfish. The cavity machining temperature was specified to be around 25 °C. The expansion ratio of OFHC copper between 20 K and 298 K, L_{298}/L_{20} = 1.0033428, was determined from the empirical approximate function for the linear thermal expansion coefficients given by NIST database. The respective dimensions of the cavity were specified to an accuracy of 0.1 µm. The cross-sectional view of the setup of the test cavity for the field measurement is shown in Fig. 3. There are no tuning structures in the cylinder walls due to structural restrictions. The on-axis electric field distribution calculated by Superfish is shown in Fig. 4. Calculation of the electron beam trajectories were carried out by using GPT, where the electric field distribution in Fig. 4 was used as the accelerating field.

The beam simulation results are shown in Fig. 5, which is based on the RF and the beam conditions listed in Table 1. The beam trajectories were calculated for 5,000 macro-particles by taking into account of the space charge effect, with the laser diameter of φ1 mm on the cathode surface. Figure 5 shows that the beam size is increasing at the exit of the cavity. In the simulation the RF phase has not been optimized for the bunch length and the energy spread. The shape of the cathode end plate should be considered if there are no focusing coils around the cavity.

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

RF frequency	5712	MHz
Source peak RF power	4	MW
Q_0	60000@20K 11000@293K	
Shunt impedance	550@20K 103@293K	MΩ/m
Coupling coefficient	20	
Cavity length	68.2	mm
RF pulse duration	2	µs
RF pulse repetition rate	50	Hz
Maximum field on axis	95	MV/m
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

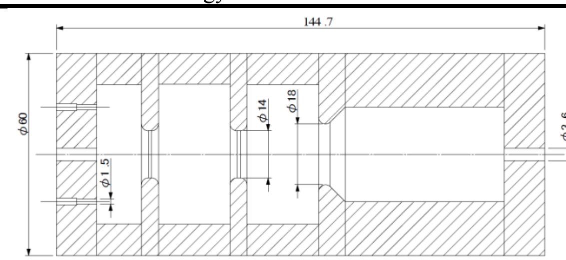

Figure 3: Cross-sectional view of the test cavity setup for field measurement prior to diffusion bonding.

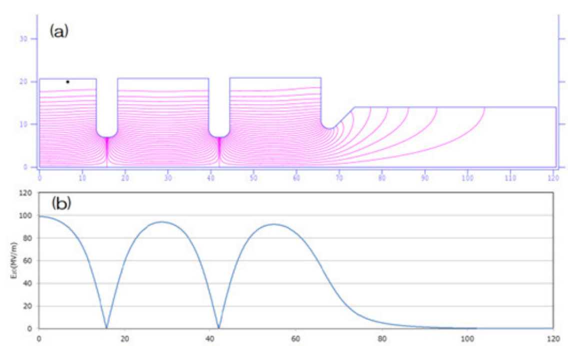

Figure 4: The π-mode electric field by the Superfish simulation. (a) Electric field,(b) On-axis electric field intensity distribution (electric field average: 70 MV/m).

FABRICATION AND MEASUREMENTS OF THE TEST CAVITY

Fabrication and Diffusion Bonding

The cavity dimensions were determined by assuming the machining temperature to be around 298 K (24.85 °C). Therefore, the resonant frequency of the cavity expected at 298 K in vacuum was 5692.970 MHz. The actual machining temperature was 23.5 °C with no corrections of the cavity dimensions for the difference of

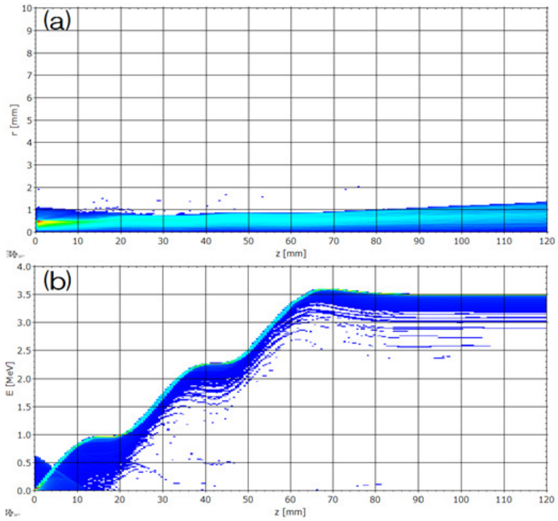

Figure 5: Simulation of the beam extraction by GPT. (a) Beam trajectory, (b) Beam energy.

1.35 °C, from which we expect the frequency shift of approximately -128 kHz from 5712 MHz at 20 K. The diffusion bonding was performed in the hydrogen furnace of KEK after the measurements of the low power RF properties at room temperature. After diffusion bonding, the entire length of the cavity was changed by -0.0127 mm.

Measurements of the Resonant Frequency and the Electric Field Distribution

The RF properties of the low power test cavity have been measured under conditions of room temperature and atmospheric pressure using a network analyzer E5071C (Keysight Technologies). The room temperature, the room humidity, the atmospheric pressure and the temperature of the cavity wall were recorded during the measurements in order to convert every measured resonant frequency to that at certain conditions. The measured resonant frequencies have been converted to the values at 23.5 °C in vacuum by using the Superfish utility code, Convertf. The separation between the π-mode and π/2-mode frequencies were approximately 20 MHz, which is consistent with the simulation by Superfish. The resonant frequency of the π-mode after diffusion bonding was 5692.601 MHz, which is approximately 120 kHz higher than that before bonding. The Q_0 value estimated from the Smith chart was 11440 after diffusion bonding, which is 20 % higher than that obtained before bonding. The Q value is in good agreement with the results of the Superfish calculation. However, the resonant frequency was nearly 370 kHz lower compared to the design value of 5692.970 MHz. The difference in the resonant frequency is partly due to the machining error in the cylinder diameters, which were on average more than 1 μm larger than the design value. The cylinder diameter errors can explain the lowering of the frequency by 150 kHz.

The electric field distribution on the axis of the 2.6-cell cavity has been measured by the bead-pull method using a metal sphere of 2 mm in diameter. The field distribution obtained from the frequency shift data is shown in Fig. 6 together with the result of simulation by Superfish, where the frequency shifts were measured at 0.5-mm intervals over the entire length of the cavity. In order to avoid the change in the frequency data by temperature, humidity, cavity temperature and atmospheric pressure changes during the run, the data taking run was repeated 10 times automatically and rapidly. As seen in Fig. 6, the electric field distribution in the 0.6-cell part is approximately 10% lower than the calculation possibly due to the existence of the antenna insertion hole. In the other part of the cavity, the electric field distribution is comparable with the calculated result.

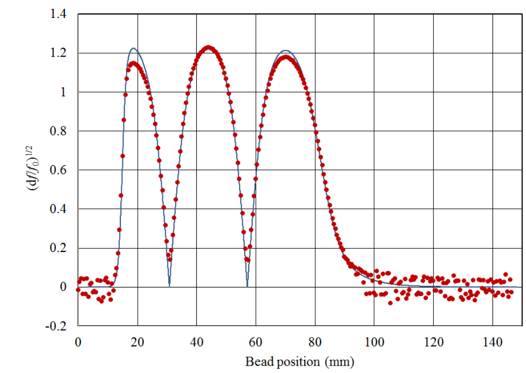

Figure 6: The π-mode electric field distribution measured by the bead-pull method. The solid curves are the result of calculation by Superfish.

CONCLUSIONS

The RF properties of the basic low power test cavity for the 2.6-cell C-band cryo-cooled photocathode RF gun has been measured at room temperature. The resonant frequency of the π-mode was 5692.601 MHz at 23.5 °C in vacuum, and the Q_0 value estimated from the Smith chart was 11440, respectively after diffusion bonding. The Q_0 value and the electric field distribution are in good agreement with the results of the Superfish calculation. The cryogenic cooling, low power test at 20 K and fabrication of the next test cavity with an RF coupler will be carried out in 2014 to 2015.

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