LOW-TEMPERATURE PROPERTIES OF 2.6-CELL CRYOGENIC C-BAND RF-GUN COLD MODEL CAVITY*

T. Sakai†, T. Tanaka, K. Nogami, K. Takatsuka, K. Nakao, M. Inagaki, LEBRA,
Nihon University, Funabashi, Japan
M. Fukuda, T. Takatomi, D. Satoh, N. Terunuma, J. Urakawa, M. Yoshida, KEK, Tsukuba, Japan

Abstract

Development of a cryogenic C-band photocathode RF gun cavity has been conducted at Nihon University in collaboration with KEK. Improvement of the RF input coupler and the 2.6-cell accelerating structure from the first cold model has been performed using the 3D simulation code CST Studio. The high-purity copper cavity was fabricated at KEK with ultraprecision machining and diffusion bonding technique. The low level RF properties of the cavity measured at room temperature have been in good agreement with the predictions based on the CST Studio calculation. The experiments of 20 K cooling of the cavity have begun at Nihon University since the late summer of 2016. Preliminary 20 K cooling tests have shown the RF properties consistent with the simulation by CST Studio.

INTRODUCTION

Development of a cryocooled 2.6-cell π-mode C-band photocathode RF electron gun has been advanced at Nihon University in collaboration with KEK [1].

In the new cold model cavity, as a major difference from the one fabricated in 2015, the corners of the new cavity cells have been modified to be rounded off for increasing RF power efficiency [2, 3]. Based on the low temperature characteristics data of high-purity copper materials available from NIST [4], the dimensions of the RF input coupler and the 2.6-cell π-mode cavity were determined by the simulations using SUPERFISH [5], CST Studio [6] and GPT [7]. The structure of the input coupler has been modified to improve the VSWR characteristics and the conversion efficiency from the rectangular TE_{10} to the circular TM_{01} mode. The cavity was completed at the Mechanical Engineering Center in KEK by ultraprecise machining and diffusion bonding technique. After low power tests at the room temperature, low temperature cooling experiments of the cavity down to approximately 20 K have been carried out at LEBRA in Nihon University since the late summer of 2016.

PROPERTIES OF THE NEW 2.6-CELL COLD MODEL CAVITY

The field simulation of the first cold model cavity with CST-Studio suggested that, in addition to a large reflection in the coupler, non-negligible TE_{11} mode electric field was excited on the circular waveguide axis. As a result of careful coupler dimension search, the TE_{11}/TM_{01} electric field amplitude ratio on the circular waveguide has been reduced from 17% to approximately 2% in the new model [8].

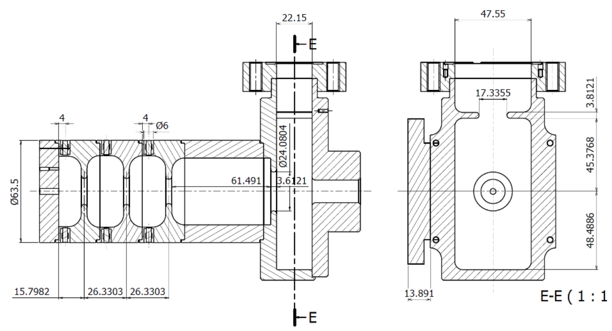

Figure 1: Cross-sectional view of the 2.6-cell π-mode cold model cavity.

The dimensions of the input coupler have also been modified to improve the VSWR characteristics and the conversion efficiency from TE_{10} to TM_{01} mode. The frequency separation from the TM_{01} π/2 mode has been expanded from 20 MHz to 46 MHz [9]. The low temperature surface resistance of the copper cavity has been estimated from the theory of the anomalous skin effect [10]. The linear expansion ratio of copper between 20 K and 296.65 K, $L_{296.65K}/L_{20K}$ = 1.0033529, was deduced from the resonant frequency shift that occurred at a cooling-test cavity, which is slightly different from the estimate obtained from the

Table 1: Specifications for the 2.6-cell Cryogenic C-band Photocathode RF Gun with Input Coupler

RF frequency @ 20 K	5712	MHz
Source peak RF power	4	MW
Q_0	73029 @ 20 K	
	13310 @ 297 K	
Shunt impedance	603 @ 20 K	MΩ/m
	113 @ 297 K	MΩ/m
Coupling coefficient	19.3 @ 20 K	
	3.52 @ 297 K	
Cavity length	68.2	mm
RF pulse duration	2	µs
RF pulse repetition rate	50	Hz
Maximum field on axis	95	MV/m
Output beam energy	0.73	MW
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

* Work supported by the Photon and Quantum Basic Research Coordinated Development Program of the Japanese Ministry of Education, Culture, Sports, Science, and Technology (MEXT).
† sakai@lebra.nihon-u.ac.jp

empirical approximate function for the linear thermal expansion coefficients given by NIST. The cross sectional drawing of the 2.6-cell π-mode cold model cavity with the circular-waveguide RF input coupler is shown in Fig. 1.

The copper material for the 2.6-cell cavity section and the circular waveguide has been 6N8 oxygen-free copper. For the end plate and the other parts C1011-6N8 oxygen-free copper has been used. An MO-type flange [11] plated with oxygen-free copper has been used for the waveguide flange.

The design specifications and the RF characteristics of the cold model cavity expected from the simulations are listed in Table 1. The Q_0, the shunt impedance and the coupling coefficient are the values obtained by the CST Studio simulation using the surface resistance at each temperature.

MEASUREMENTS ON THE 2.6-CELL COLD MODEL CAVITY

Experimental Setup of the Cavity

The experiment has been carried out using a cryogenic cooling system and a vacuum chamber prepared at LEBRA. The cryogenic cooling system consists of a rectangular vacuum chamber and a refrigerator unit (SUZUKI SHOKAN Co., Ltd. 20 K GM type [12]) installed on it at the base wall. The 2.6-cell cavity has been attached to the cold head of the refrigerator unit via a copper base plate and a copper heat sink as shown in Fig. 2.

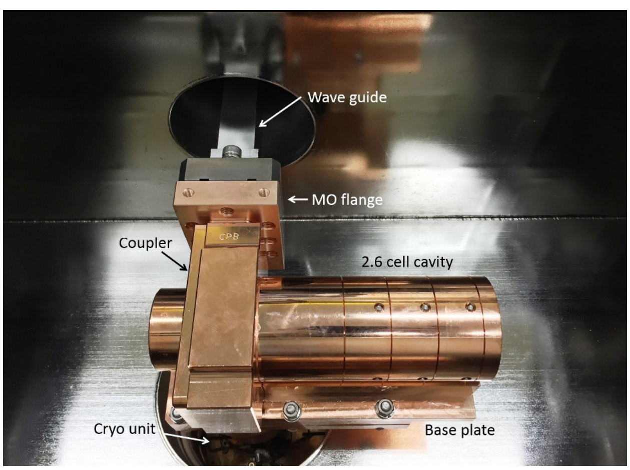

Figure 2: Photograph of the cold model 20 K 2.6-cell cavity. The RF power is fed into the cavity through the thin-wall stainless steel waveguide to avoid a large thermal flow.

The silicone thermal grease (Apiezon N Cryogenic High Vacuum Grease [13]) has been applied to both sides of the base plate to improve the thermal conductance between the cavity and the heat sink. The cavity temperature has been monitored using semiconductor temperature sensors (Lake Shore Cryotronics Inc., DT-670 [14]) attached to the base plate and each end of the cavity. The resonant frequency has been deduced from the $|S_{11}|$ measurements using a network analyser (Keysight Technologies E5071C). The RF power from the network analyser has been fed into the cavity through a thin-wall stainless steel thermal gradient waveguide (approximately 400 mm long) in order to avoid a large thermal flow, after transmitted with a coaxial cable (Junkosha, JUNFLON (R) MWX021 [15]) and converted to the waveguide mode with a coaxial-waveguide converter. Calibration of the network analyser has been carried out at the end of the coaxial-waveguide converter using a Waveguide Calibration Kit.

Resonant Frequency at 20 K

The cavity cooling experiment was begun after the vacuum chamber was ready for turbo-molecular pumping. During the cooling process, the π-mode resonant frequency was traced and saved automatically to a PC every 30 sec together with the cavity temperature, the $|S_{11}|$ spectrum, the Smith chart and the VSWR around the resonance peak. Changes in the cavity temperature and the π-mode resonant frequency measured during the cooling experiment from the room temperature down to around 20 K are shown in Fig. 3 as a function of the time elapsed since the refrigerator was turned on.

The cavity was cooled from 293.88 K to 20.20 K spending approximately 30 hours, then came to a steady temperature. During the period the π-mode resonant frequency has varied from 5693.120 MHz to 5711.895 MHz. The resonant frequency at 20 K is approximately 100 kHz lower than the result of the CST Studio simulation.

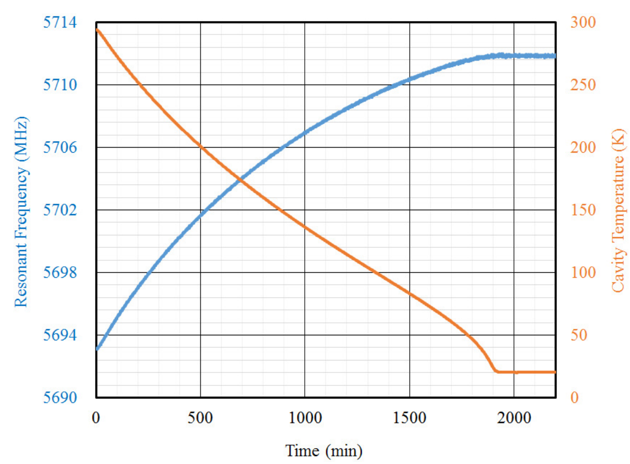

Figure 3: Plot of the cavity temperature and the π-mode resonant frequency as a function of the time since the cooling started. The cooling of the cavity took 30 hours, then the resonant frequency reached a constant value of 5711.895 MHz.

The Temperature Change of the Q Value

The $|S_{11}|$ spectrum at the lowest temperature (20.20 K) is shown in Fig. 4. The fitting curve in the figure shows the resonance curve calculated using the resonant frequency f_0= 5711.895 MHz, the coupling coefficient β = 19.4 and the loaded Q-value Q_L= 3300, which is in agreement with the measured spectrum near the resonant peak. In this preliminary analysis of the $|S_{11}|$ spectrum, the unloaded Q-

ISBN 978-3-95450-169-4

value Q_0 is estimated to be approximately 68000, which is slightly low compared to the designed value. On the other hand, the coupling coefficient β of 19.4 is in agreement with the designed value.

The effects of the adjacent modes in the circular waveguide or the errors in the waveguide calibration have not been taken into consideration in the resonance curve fitting. Precise measurements and detailed analyses are expected to reproduce the resonance curve and allow to estimate more accurate properties.

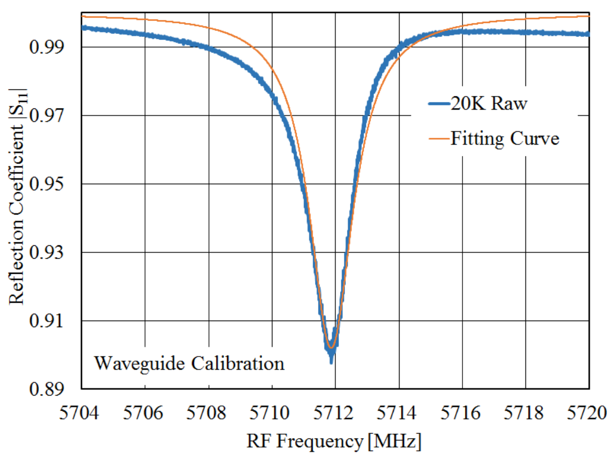

Figure 4: Reflection coefficient $|S_{11}|$ spectrum measured at the cavity temperature of 20 K.The Q_0 value of approximately 68000 has been deduced from the spectrum with the loaded-Q value of 3300 and the coupling coefficient β of 19.4.

CONCLUSIONS

A cryo-cooled 2.6-cell π-mode C-band photocathode RF electron gun has been developed by the collaboration between KEK and LEBRA at 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).

Preliminary 20 K cooling tests of the new 2.6-cell cold model cavity have been performed by the low power RF feeding through a thin-wall stainless steel waveguide. The cavity was cooled from 293.88 K down to 20.20 K spending approximately 30 hours. The π-mode resonance frequency has varied from 5693.120 MHz to 5711.895 MHz. The resonance frequency at 20 K has been approximately 100 kHz lower than the CST Studio calculation. The Q_0 value of approximately 68000 resulted from an analysis of the $|S_{11}|$ spectrum has been slightly lower than the design value. More precise experiments and detailed analyses of the cavity are planned in 2016. On the basis of the cold model experiment, the design and fabrication of a high-power model cavity is under consideration.

REFERENCES

[1] M. Fukuda *et al.*, "Status and future plan of the development of a compact X-ray source based on ICS at laser undulator compact X-ray (LUCX)", in *Proc. 5th Int. Particle Accelerator Conf. (NA-PAC'13)*, Pasadena, USA, Sep. 2013, paper TUPMA01, pp. 589-592.

[2] T. Tanaka *et al.*, "RF input coupler for 20 K cooled C-band 2.6-cell photocathode RF gun", in *Proc. 6th Int. Particle Accelerator Conf. (IPAC'15)*, Richmond, VA, USA, May. 2015, paper WEPWA015, pp. 2522-2525.

[3] T. Tanaka *et al.*, "Low temperature properties of 20 K cooled test cavity for C-band 2.6-cell photocathode RF gun", in *Proc. 6th Int. Particle Accelerator Conf. (IPAC'15)*, Richmond, VA, USA, May. 2015, paper WEPWA014, pp. 2519-2521.

[4] NIST, http://cryogenics.nist.gov/MPropsMAY/OFHC%20Copper/OFHC_Copper_rev.htm

[5] J. H. Billen and L. M. Young, LA-UR-96-1834 (2006), Los Alamos National Laboratory, http://laacg.lanl.gov/laacg/services/download_sf.phtml

[6] CST Studio Suite™, CST AG, Germany, http://www.cst.com

[7] Pulsar Physics, http://www.pulsar.nl/gpt/index.html

[8] K. Takatsuka *et al.*, "Optimization of C-band RF Input Coupler as a Mode Converter for 20-K Cryocooled Photocathode RF Gun", in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May. 2016, paper WEPMY038, pp. 2638-2640.

[9] T. Sakai *et al.*, "Cold Model Cavity for 20-K Cryocooled C-band Photocathode RF Gun", in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May. 2016, paper WEPMY037, pp. 2635-2637.

[10] G. E. H. Reuter and E. H. Sondheimer, "The theory of the anomalous skin effect in metals",in*Proc. the Royal Society of London A, Mathematical and Physical Sciences*, Vol. 195, No. 1042, pp. 336-364, 1948.

[11] Ohtsuka Inc., http://mo-ohtsuka.co.jp/moflange.html

[12] Suzuki Shokan Co., Ltd., http://www.suzukishokan.co.jp/english/cryogenic_3.html

[13] M&I Materials Ltd., http://www.apiezon.com/products/vacuum-greases/n-grease

[14] Lake Shore Cryotronics Inc., http://www.lakeshore.com/products/cryogenic-temperature-sensors/silicon-diodes/dt-670

[15] Junkosha Inc., http://www.junkosha.co.jp/english/products/cable/c06.html