OPTIMIZATION OF C-BAND RF INPUT COUPLER AS A MODE CONVERTER FOR 20-K CRYOCOOLED PHOTOCATHODE RF GUN*

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

Abstract

The design of the input coupler for the cryocooled 2.6-cell C-band photocathode RF gun has been modified in the new cold model cavity. In the design calculation of the previous one, the diameters of the last accelerating cell, the circular waveguide and the coupling iris between the circular and the rectangular waveguides were adjusted simultaneously to satisfy the specifications of the RF gun. As a result this method has led to uncertain coupling coefficient between the accelerating cavity and the circular waveguide. In the new model, the input coupler has been independently designed as a low-reflection and low-insertion loss converter from rectangular TE_{10} to circular TM_{01} mode, which allows us to estimate the coupling coefficient from the measurement of the reflection coefficient at the input port of the rectangular waveguide.

INTRODUCTION

Development of a cryocooled 2.6-cell C-band photocathode RF gun has been underway at Nihon University in collaboration with KEK [1]. The RF gun cavity made of 6N8 high purity copper is expected to have high acceleration efficiency and frequency stability due to low surface resistance and low thermal expansion at a low temperature of 20 K [2, 3]. The RF power is provided through the input coupler that consists of a rectangular waveguide and a circular waveguide located along the accelerating cavity axis [4, 5]. Figure 1 shows the cutaway view of the input coupler. The combination of these waveguides has been designed to work as an RF transmission mode converter from rectangular TE_{10} to circular TM_{01} mode. The circular waveguide is connected to the end cell of the accelerating cavity. The coupling coefficient at the RF input port is chosen to be approximately 20 at 20 K in order to reduce the build-up time of the field in the cavity to around 200 ns. After the RF property measurement on the first test model, designs of both the coupler and the 2.6-cell cavity have been modified. In this paper an improved design of the coupler obtained by the CST-Studio simulation [6] is discussed.

NEW COUPLER DESIGN

In the design of the first cold model of the RF gun cavity, the π-mode resonant frequency and the coupling coefficient were finally adjusted by the dimensions of the diameters in the last accelerating cell, the circular waveguide and the circular coupling iris between the circular and the rectangular waveguides. Though the apparent coupling coefficient at the input port of the rectangular waveguide was adjusted to around 20 of over coupling, this method had changed the coupling between the rectangular and the circular waveguides considerably. From the CST-Studio calculation of the transmission to the circular waveguide without connection to the 2.6-cell cavity, the VSWR at the input port was estimated to be 3.25 at room temperature and slightly higher at 20 K. On the other hand, at the circular waveguide when simulated as an input port to the 2.6-cell cavity the VSWR was 1.4 at room temperature and 7.8 at 20 K, respectively. These simulations have suggested that it is difficult to measure the coupling coefficient between the 2.6-cell cavity and the circular waveguide unless the RF reflection power in the coupler is sufficiently small.

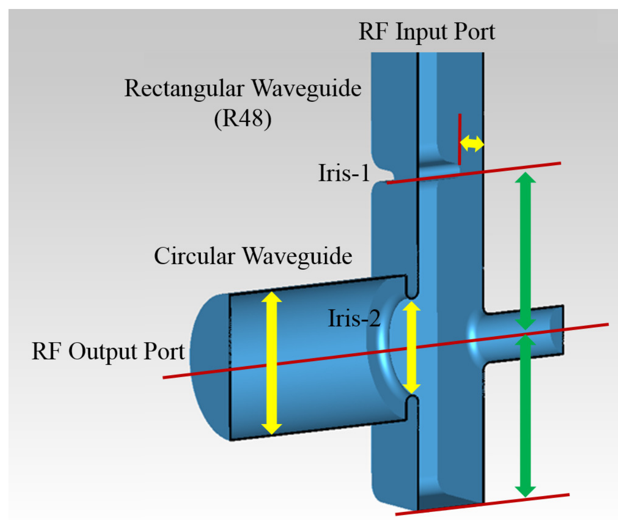

Figure 1: Cutaway view of the RF input coupler in the CST-Studio calculation of the transmission property. The arrows indicate the dimensions optimized for an ideal mode converter.

After the low-temperature test on the first cold model cavity, the design of the coupler has been reviewed. In addition to the large reflection in the coupler, the simulation suggested that the TE_{11} mode electric field was considerably strong on the circular waveguide axis.

An ideal mode converter can be defined as a device with no insertion loss, no reflection loss and no other modes than specified are transmitted. For the suppression of the reflection and improvement in the efficiency of conversion from the rectangular TE_{10} to the circular TM_{01} mode in the

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

new coupler, most of the dimensions of the coupler structure have been parametrized in the CST-Studio simulation. While the thickness in the irises was fixed to 3.6 mm, the dimensions indicated by the arrows in Fig. 1 have been optimized for a low VSWR and a low TE_{11}/TM_{01} electric field amplitude ratio on the circular waveguide axis to be satisfied simultaneously at the accelerating frequency.

The length and the diameter of the circular waveguide are not critical in the optimization for the coupler properties. They are rather critical in the determination of the frequencies of TM_{01} modes excited in the circular waveguide. These modes should be separated from the accelerating frequency. Therefore, these dimensions have been determined by another simulation of the whole RF gun system consisted of the 2.6-cell cavity and the coupler [7].

RESULT OF SIMULATION

The transmission and reflection property in the coupler has been obtained from the calculation of the RF power flow by setting the left-end of the circular waveguide in Fig.1 to the output port with no reflection. Figure 2 shows the result of the coupler optimization, where S_{11} is the reflection coefficient of the input TE_{10} mode at the input port, S_{21} (TM_{01}) and S_{21} (TE_{11}) being the transmission coefficients at the output port for TM_{01} and TE_{11} modes, respectively. A copper surface resistance of 3.541×10^{-3} Ω at 20 K has been assumed in the calculation. The lowest VSWR deduced from S_{11} is 1.01 at around the accelerating frequency of 5712 MHz as shown in Fig. 3. The VSWR has not significantly changed even in the simulation using a room-temperature surface resistance of 1.9955×10^{-2} Ω. The transmitted power estimation has suggested that 99.6 % of the input power can be converted to TM_{01} mode.

Figure 4 shows the electric field distribution in the coupler, where the RF is nearly at the phase that the field in the rectangular waveguide reaches its maximum strength. The electric field amplitudes of TM_{01} and TE_{11} modes on the circular waveguide axis are shown in Fig. 5. The amplitudes correspond to an input RF power of 1 W. The constant amplitudes in the circular waveguide are due to the boundary condition that there is no reflection on the left-end of the circular waveguide i.e., no standing wave.

The TE_{11}/TM_{01} electric field amplitude ratio on the circular waveguide is shown in Fig. 6, where the result in the simulation of the first model is compared. The ratio was approximately 0.17 in the first model. As a result of optimization, it has been reduced to approximately 0.02 in the second model. The ratio could be decreased further by reducing the diameter of the circular iris, Iris-2, in Fig. 1.

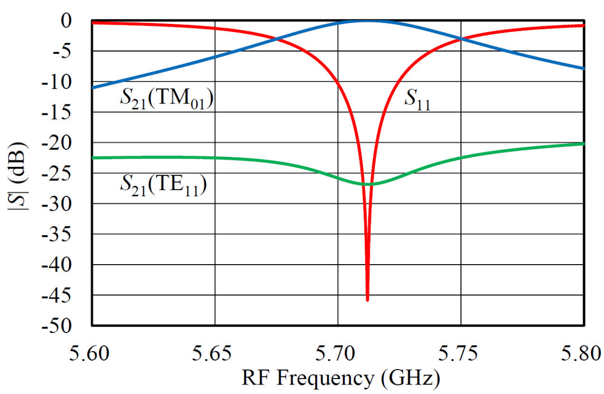

Figure 2: The result of the CST-Studio calculation optimized for the coupler with low reflection, low insertion loss and high conversion efficiency to TM_{01} mode.

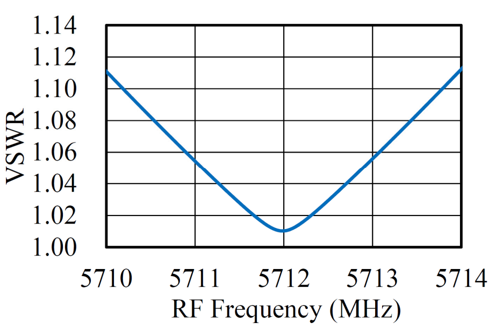

Figure 3: The VSWR obtained by the CST-Studio simulation at around the accelerating frequency of 5712 MHz.

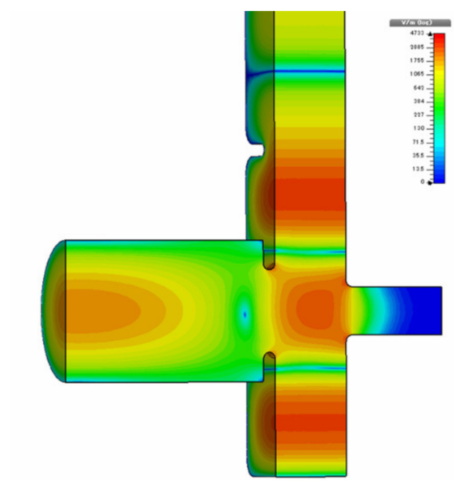

Figure 4: The electric field distribution in the coupler obtained by CST-Studio at 5712 MHz.

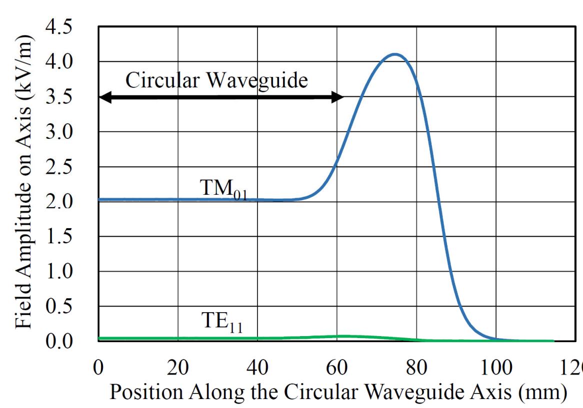

Figure 5: The electric field amplitudes of TM_{01} and TE_{11} modes on the axis of the circular waveguide. The amplitudes correspond to an input power of 1 W.

ISBN 978-3-95450-147-2

However, it could cause a trade-off with the VSWR that has already been adjusted to be very low.

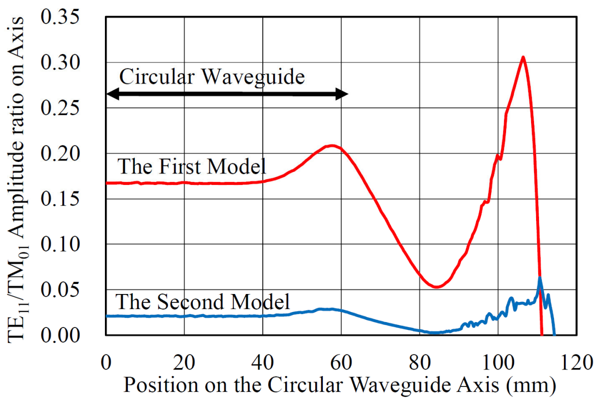

Figure 6: The TE_{11}/TM_{01} electric field amplitude ratios on the circular waveguide axis of the first and the second models.

EFFECT OF DIMENSION ERRORS

The RF gun test cavity is machined by ultraprecise machining technique at KEK. The machining error in each specified dimension is expected to be within 1 μm. The dependences of the shifts in the lowest VSWR and its frequency on the dimension error have been simulated using CST-Studio by changing each coupler dimension individually within a range of ±2 μm. The results are shown in Figs 7 and 8, where the dimensions indicated are the rectangular waveguide width (RW_w), the gap in Iris-1 (Iris-1_g), the distance of Iris-1 from the beam axis (Iris-1_h), the thickness in Iris-1 (Iris-1_t), the circular waveguide diameter CW_d), the Iris-2 diameter (Iris-2_d), the bottom depth in the rectangular waveguide (RW_btm) and the thickness in Iris-2 (Iris-2_t), respectively.

The result suggests that the lowest VSWR is insensitive to the errors. The error of ±2 μm causes only small difference within $\pm 7\times10^{-4}$ for each dimension. The sum of the maximum VSWR changes in all the dimensions is approximately 0.002, which is negligibly small. The frequency of the lowest VSWR is sensitive to RW_w, Iris-1_h and Iris-1_t. The sum of the maximum frequency shifts is approximately 300 kHz, which could cause an increase in the

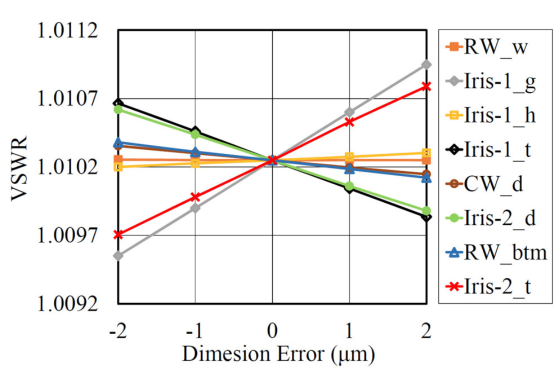

Figure 7: Change in the lowest VSWR due to errors in the individual coupler dimension.

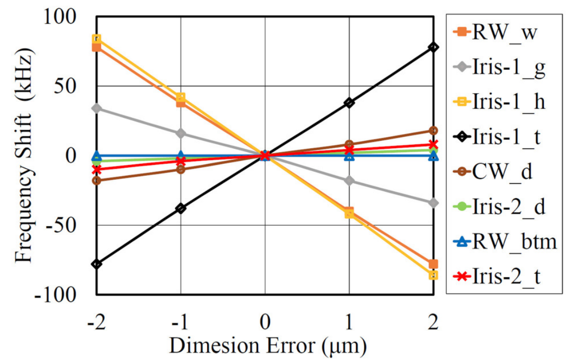

Figure 8: Shift in the VSWR-lowest frequency due to errors in the individual coupler dimension.

VSWR from 1.01 to 1.02 at the normal accelerating frequency as predicted from the VSWR curve in Fig. 3. The TE_{11}/TM_{01} field amplitude ratio is not expected to change significantly by the frequency shift, since the power transmission coefficients in the coupler are rather slow functions of frequency as seen from the S_{21} curves in Fig. 2.

CONCLUSIONS

The RF input coupler of a cryocooled C-band 2.6-cell photocathode RF gun has been optimized for a low VSWR and a low TE_{11}/TM_{01} electric field amplitude ratio on the circular waveguide axis. The coupler is expected to work as an efficient mode converter. The analysis of the dimension errors in the ultraprecise machining process suggests that an error of ±2 μm would have only negligibly small effects on the coupler properties.

REFERENCES

[1] T. Tanaka *et al.*, "Basic design of a 20K C-band 2.6-cell photocathode RF gun", *in Proc. 5th Int. Particle Accelerator Conf. (IPAC'14)*, Dresden, Germany, Jun. 2014, paper MOPRI030, pp. 658-660.

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

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

[4] Y. Taniguchi *et al.*, "Development of X-band thermionic RF electron gun using choke structure", *in Proc. 5th Annual Meeting of Particle Accelerator Society of Japan*, Higashihiroshima, Japan, Aug. 2008, paper TP115, pp. 954-956.

[5] 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.

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

[7] T. Sakai *et al.*, "Cold model cavity for 20-K cryocooled C-band photocathode RF gun", presented at the 7th Int. Particle Accelerator Conf. (IPAC'16), Busan, Korea, May 2016, paper WEPMY037, this conference.