DEVELOPMENT OF AN L-BAND RF GUN FOR HIGH-DUTY-CYCLE OPERATION

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Abstract

The development of a laser-photocathode L-band RF gun at a 1.3 GHz frequency is in progress, which can withstand the average input RF power of 25 kW. We adopt a 1.5 cell DESY-type RF cavity with a coaxial input coupler. The cooling system of the RF cavity is designed so that the temperature rise of the cavity is made not higher than 5ºC for the maximum input power. The RF cavity is made by brazing various components and most critical process is brazing for assembling three parts for the main body of the RF cavity so that filler metal does not overflow to the inner surface of the RF cavity but it fills all the available space between the parts to ensure mechanical strength and vacuum tight. Some brazing tests are conducted and empirical guiding principles for such brazing are derived. Based on these principles, a final test for brazing is successfully made.

INTRODUCTION

We began development of a laser-photocathode L-band RF gun in 2008 that can generate a high-intensity and high-brilliance electron beam to advance studies with the L-band electron linac at the Institute of Scientific and Industrial Research (ISIR), Osaka University in collaboration with the High Energy Accelerator Organization (KEK) and Hiroshima University. In this study, we are also commissioning another L-band RF gun of the DESY type used for beam acceleration experiments at the Superconducting RF Test Facility (STF) at KEK in parallel with the design and fabrication of the new RF gun.

In 2008, we conducted computer simulation of a 1.5 cell RF cavity of the DESY-type RF gun [1] using SUPERFISH in preparation for adjusting the resonance frequency and the field balance of the RF cavity that was at that time being fabricated at the Fermi National Accelerator Laboratory (FNAL), investigated a wave guide-to-coaxial line converter for the input coaxial coupler, and calculated characteristics of the electron beam from the RF gun to design the solenoid magnet for emittance correction in the RF gun [2]. In 2009, we conducted the conceptual design of the new RF gun with the emphasis on its cooling system that can withstand the average input RF power of 25 kW. The RF cavity fabricated at FNAL was temporarily taken to KEK to adjust the resonance frequency and the field balance, and sent back to FNAL for completion by installing the water-cooling pipes. We designed and fabricated the solenoid magnet for the DESY-type RF gun and various magnets used for the STF beam line. In this paper, we will report the design of the cooling system of the RF cavity and progress of its fabrication.

COOLING SYSTEM

Basic Design

All the input RF power reaching 25 kW is converted to the heat loss on the inner wall of the cavity. The problem is a shift of the resonance frequency of the cavity owing to the temperature rise. If the frequency shift exceeds the bandwidth determined by the Q-value of the cavity, it is not possible to feed the RF power further to the cavity. The frequency shift due to the temperature rise Δf is –21.5 kHz/ºC calculated with the thermal expansion coefficient of copper, which agrees quite well with the value of 22 kHz/ºC measured at DESY. The unloaded Q-value of the 1.3 GHz, 1.5 cell cavity is approximately $Q_0 = 23{,}000$ and if the coupling factor β is equal to 1.0 the loaded Q-value will be $Q_L = 11{,}500$, from which the allowable frequency shift is calculated to be $\Delta F_Q = 1.3\ \mathrm{GHz}/11{,}500 = 113\ \mathrm{kHz}$. The acceptable temperature rise of the cavity is then

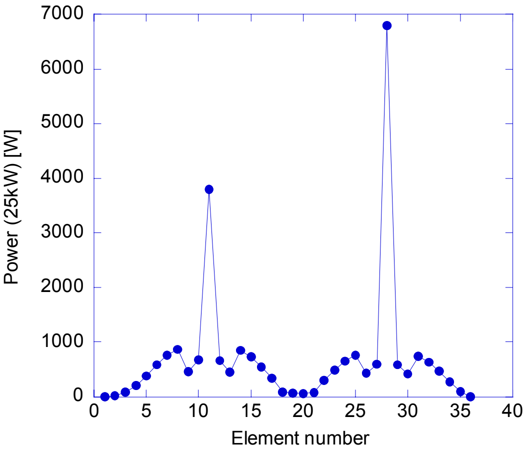

Figure 1: Power loss on the RF cavity wall.

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derived as ΔT_{cavity} = 5.3ºC. The thermal conductivity coefficient from copper to water is h = 9.8 ~ 8.5 kW/(m^2·K) for a water pipe of 10~20 mm in diameter. The area of contact between copper and water needs to be 0.5 m^2 so as to take the heat load of 25 kW from the RF cavity with the temperature difference of 5 ºC. The temperature rise of cooling water after cooling the cavity should be much smaller than that of the cavity, 5 ºC to keep the cavity temperature uniform. The total water flow is calculate to be 358~723 liter/min necessary for taking the power of 25 kW with the temperature rise of 0.5~1ºC, which is 10~20 % of the temperature rise of the cavity. The maximum water flow is reported to be 2 m/s to avoid erosion of copper surface with water [3], so that the total cross-sectional area of the water channels will be 30~60 cm^2.

Heat Loss

We calculated the surface power loss of the 1.5 cell RF cavity with SUPERFISH. The cavity has an axially symmetric structure and the inner surface is divided into 26 regions. Figure 1 shows the power generated in each area for the total power input of 25 kW. The two peaks appearing at the numbers 11 and 28 show power dissipation of 4 and 7 kW on the cylinder walls of the half and the full cells, respectively. The power loss in the two broad bases of the peaks, which correspond to the endplates, is more or less the same and it is approximately 3.5 kW/area.

Water Channels

Figure 2 shows water channels of the cooling water system for the RF cavity designed to take the heat load off in each area based on the consideration made in *Basic Design* and the heat distribution shown in Fig. 1. In order to make sure of heat conduction through copper, the water channels are 10 mm wide and the space between them is 10 mm, while they are 20 mm deep in the cylindrical parts and 25 mm deep on the two endplates for increasing the interface area between copper and water. All the water channels in the cylinder parts are parallel and independent; the water flow is only one-turn around the cavity body. The water channels on the end plates is shorter than those on the bodies owing to shorter radiuses with respect to the beam axis, so that those on the end plates are 25 mm deep to make the interface area enough to take the heat with temperature difference of 5ºC. The problem is the two endplates of the wall with the iris separating the half and the full cells. In spite that the heat is generated on both sides of the wall, only one water-channel can be made as shown in Fig. 2, so that the interface area is not sufficient to keep the temperature rise lower than 5ºC. In order to make it larger, many parallel triangular-shaped, 1 mm deep trenches are machined at 1 mm intervals on the inner surfaces of the water channel so that the surface area is made approximately two times larger. Figure 3 shows the temperature distribution of the RF cavity calculated with the finite element method for the RF power input of 25 kW CW. The temperature rise of the inner surface of the cylindrical body, to which the resonance frequency is very sensitive, is 4~5ºC, while the temperature rise reaches 8.2ºC in some parts of the endplates (red spots). The area of the highest temperature part on the iris (yellow, +5ºC) is smaller than those on the opposite endplates due to the corrugated inner surface of the water channel. The temperature rise would exceed 10ºC without it, which does not meet the requirement. The thermal expansion of the RF cavity due to the temperature rise is approximately 6 μm in the longitudinal direction and the radial expansion is 4 μm, so that its effects on the resonance frequency are negligibly small.

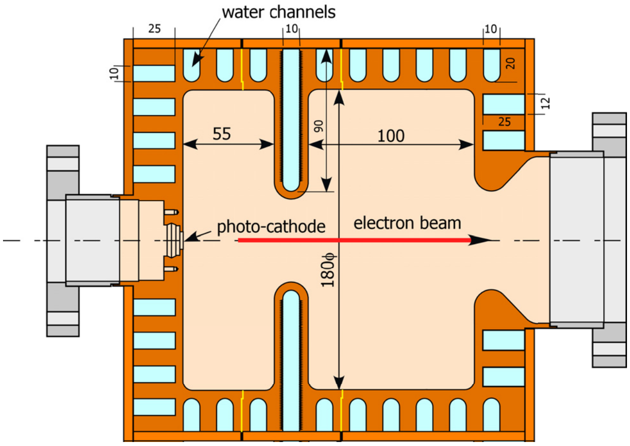

Figure 2: Water channels in the RF cavity.

BRAZING TEST

The main mechanical parts of the L-band RF cavity are the main body of the RF cavity, covers for the water channels, inlets and outlets of the water channels, and two vacuum flanges for the cathode plug and for the coaxial input coupler with the beam pipe. The main body and the covers are made of the class-1 oxygen-free copper by mechanical processing. The water inlets and outlets as well as the vacuum flanges are made of the stainless steel.

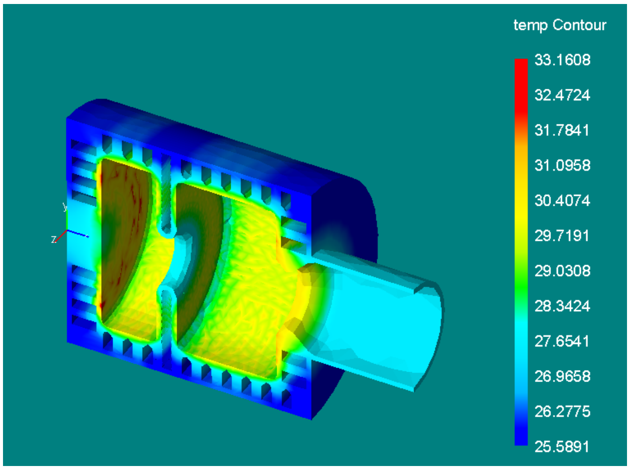

Figure 3: Temperature of the RF cavity.

Three parts for the main body is separately machined as shown with the yellow lines and the cylindrical covers and the circular plates for the water channels are first brazed with the corresponding parts of the main body. Then the three parts of the RF cavity are tentatively assembled to measure the resonance frequency precisely and based on the measurement the inner surfaces of the cylindrical parts are slightly shaved to tune the frequency to the design value. The three parts are then assembled with brazing to make the main body. Finally the water inlets and outlets as well as the vacuum flanges are attached with brazing. Among these three brazing processes, the second process for assembling the main body of the RF cavity is most important, so that we are conducting brazing tests using model pieces of connecting parts.

Our concern about brazing is that the filler metal might leak out to the inner surface of the cavity if the filler metal is too much or that brazing is not sufficient due to its shortage. We made several tests and developed the following empirical guiding principles for brazing.

- Since the filler metal fills a gap between connecting components with capillary action, the filler metal flows better though a narrower gap.
- The filler metal does not remain in a trench for it.
- The outflow of the filler metal to the outer surfaces is comparable with a gap between the connecting components if the filler metal is not excessive too much.
- The excessive filler metal leads to larger outflow to the outer surfaces.
- A space for stopping flow of the filler metal does not work and the filler metal goes through the space on the other side of the space.

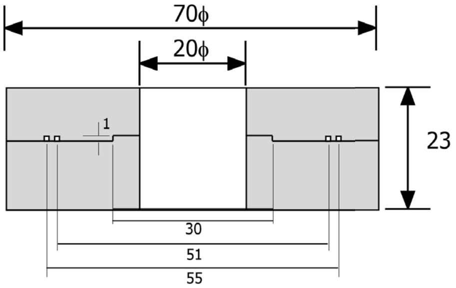

Figure 4: Cross section of copper sample for brazing test.

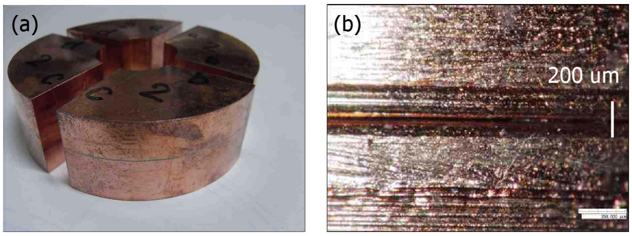

Figure 5: Test sample for brazing with 120 % filler metal. (a) Outer view of the test sample cut into four pieces and (b) close-up view of the inner surface at the brazing plane.

Based on these principles, we made test pieces, a drawing of which is shown in Fig. 4. The test piece is 70 mm in diameter though the outer diameter of the RF cavity is 230 mm. Its inner diameter is chosen to be 20 mm to make the radial profile and the dimension of the connecting part same as those of the RF cavity. The 1 mm high steps for insertion are made to make axes of the connecting components on the central line of the RF cavity. The connecting surfaces on the inner side on the steps are machined with the root-mean-square roughness of less than 200 nm using a single-crystal diamond bite and the two parts touch each other on this surface so that the gap on the inner side of the test piece is minimal. The gap on the outer side of the steps is designed to be 30 µm and the clearance for fit at the step is 20 µm on one side. The two trenches of sizes 0.9 by 0.9 mm^2 for the filler metal are made on the upper part at the position where the space for the filler metal is evenly divided. The sizes of the test piece are precisely measured using a 3-dimensional measurement system and the volume of the gap for the filler metal is calculated. We use a Pd alloy wire of 0.8 mm in diameter for filler metal. We made three tests with different amount of filler metal wit respect to the space between two parts, not including the trenches; 100, 120, and 160 %.

The three test pieces were brazed in a vacuum furnace. The temperature of the pieces was raised to 840ºC, which is 30ºC higher than the temperature of the liquidus line of the filler metal, and it was held for 10 minutes. Each test piece was cut to four equal parts as shown in Fig. 5(a) and the inner and the outer surfaces as well as the cross section were observed with a video-scope. Figure 5(a) shows a photograph of the test piece with 120 % filler metal. The line of the brazing plane is dimly seen, indicating that the filler metal slightly leaks out to the outer surface. For the test piece with 160 % filler metal, the whole outer surface of the lower cylindrical part is coated with the filler metal flowing out from the brazing surface, while the filler metal exudes slightly larger for the 100 % case than for the 120 %, the reason of which is not known. Figure 5(b) shows a close-up picture of the inner surface of the 120 % sample. We do not see any leakage of the filler metal from the brazing surface. It is confirmed the empirical guiding principles works perfectly for the test pieces. We will braze the RF cavity with 120 % filler metal.

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