VERTICAL COLD TEST OF THE CRAB CAVITY WITH A CO-AXIAL BEAM PIPE

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Abstract

A crab cavity was designed for the KEKB electron-positron collider-accelerator. The aim of this cavity is to deflect the beam bunch and realize the crab-crossing scheme. The cavity, operating in the TM110 mode, has a squashed cell with a co-axial beam pipe coupling scheme to extract the lowest order mode (TM010). Operating voltage should be high enough to deflect a beam bunch for a finite beam-crossing angle. For the R&D of this complicated structure, we have fabricated a prototype cavity and a simplified inner conductor for the co-axial beam pipe structure. We tested the RF performance of the cavity with the inner conductor in a vertical cryostat. During the tests, a serious Q-degradation was observed, which is so called "Hydrogen Q-disease". A calorimetric RF loss measurement showed that the loss at the inner conductor is a cause of the Q-degradation. We applied a quick cool-down procedure to the inner conductor and achieved a required deflecting voltage.

1 INTRODUCTION

A crab cavity was designed for the KEKB positron-electron double-ring collider accelerator [1]. The aim of the cavity is to deflect the beam bunch and realize the crab-crossing scheme [2,3]. The finite angle of the beam collision is 11 mrad x 2 and the required deflecting voltages are 1.44 MV and 1.41 MV for electron high energy ring (8GeV) and positron low energy ring (3.5GeV), respectively. The designed cavity [4] has a squashed cell with a racetrack cross section and a co-axial beam pipe coupler for the unwanted mode damping. A surface peak field is 21 MV/m at the required deflecting voltage.

To develop a crab cavity with such a complicated structure, and operating at high fields, we have fabricated a 1/3-scale model and studied RF properties [5]. Then we fabricated a full-scale prototype cavity [6]. This cavity was tested in the vertical cryostat [7]. After several improvements, we achieved the required voltage with a sufficient margin [8,9].

The cavity has a co-axial coupler in the beam pipe. The operating mode (TM110, 508MHz) is not the fundamental mode (TM010). The TM010 mode can couple with the co-axial coupler as the TEM mode and propagates down to a RF absorber. Since a design for the co-axial coupler is relatively long and has several RF components, it is impossible to set the designed coupler in a vertical cryostat. We made a simplified inner conductor for the co-axial coupler to meet space requirements of the vertical cryostat. During the cold tests, we observed Q-degradations. The unloaded Q degraded with decreasing cool-down speed. This degradation is so called "Hydrogen Q-disease" [10]. To identify the location of the Q-degradation, a calorimetric RF loss measurement was carried out. The measurement showed the inner conductor is a cause of the Q-degradation. It was shown that this type of degradation was cured when the cavity was warmed up above 200 K for more than 2 hours [11]. We warmed up the inner conductor while the cavity was kept cold. The unloaded Q recovered and we achieved the required deflecting voltage.

In this paper, we present vertical cold test results of the prototype crab cavity with a co-axial beam pipe coupler.

2 SQUASHED CELL AND CO-AXIAL COUPLING DESIGN

An original design of the crab cavity was for 500MHz, so we slightly modified the long axis of the squashed cell to give a resonant frequency of 508MHz. Cross section of the cavity cell is shown in Fig. 1. The operating mode is a TM110 mode (crab mode). Field orientations of E and B are shown in the same figure. RF parameters of the cavity were calculated using the computer code MAFIA and listed in Table 1.

Table 1: RF parameters of the crab cavity

fo (MHz)	508
R/Q (Ω)	46.2
Γ	220
Esp/Vkick (MV/m/MV)	13.5
Hsp/Vkick (Oe/MV)	424

Since the crab mode is not the fundamental mode (TM010), a co-axial coupler is adopted in a beam pipe. Fig. 1 shows a design of the co-axial coupler. The TM010 mode couples the co-axial coupler as the TEM mode and propagates down to the RF absorber. The cut-off frequency of the co-axial coupler is set at 600MHz, which give an attenuation of 60 dB/m to the crab mode. The higher order modes have frequencies above 600 MHz. These modes can propagate down to a RF absorber. From a miss-alignment of the inner conductor, the crab mode can couple the co-axial coupler as the TEM mode, which propagates without attenuation. A crab mode rejection

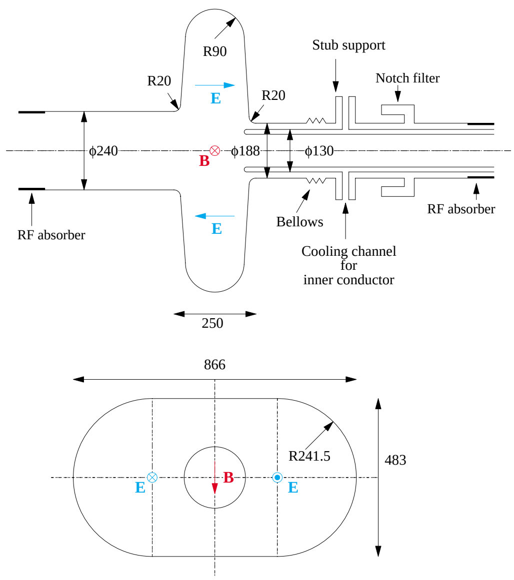

Figure 1: Squashed cell and co-axial beam pipe coupler.

filter (notch filter) is attached to the beam pipe to push the TEM-coupled crab mode back to the cavity.

To support a long inner conductor, a stub support is attached as shown in Fig. 1. The support also provides a cooling channel. The inner conductor is cooled by liquid helium through this cannel.

From a structure analysis using the finite element analysis code ANSYS, four ribs were attached at the cavity iris for reinforcement. It is impossible to tune the cavity by deforming the cavity cell. On the other hand, frequency shifts by insertion of the inner conductor. From the MAFIA calculation, frequency shift is 30kHz per 1 mm of conductor insertion. We use this frequency shift for tuning. Bellows is added to the outer conductor of the co-axial beam pipe to allow the insertion of the conductor.

3 SIMPLIFIED INNER CONDUCTOR

Since the co-axial coupler has a long and complicated structure, we made a simplified inner conductor for the vertical cold test. This is a short conductor to fit the vertical cryostat. Fig. 2 shows a layout of the inner conductor set in the cavity. The conductor has a length of 776 mm. Outer and inner diameters are 130 mm and 100 mm, respectively. The inner pipe is terminated at 65 mm from the top of the conductor. A cooling space is provided between the inner and outer pipes. The flange has a diaphragm structure, which allow the tip of the conductor to deflect +/- 5mm.

The inner conductor was made of niobium from TOKYO denkai, (RRR=200). The tip and the inner pipe were machined, while the outer pipe was made by flow forming. These components were combined by electron beam welding (EBW). A diaphragm structure was machined after fabrication. Surface treatments are almost

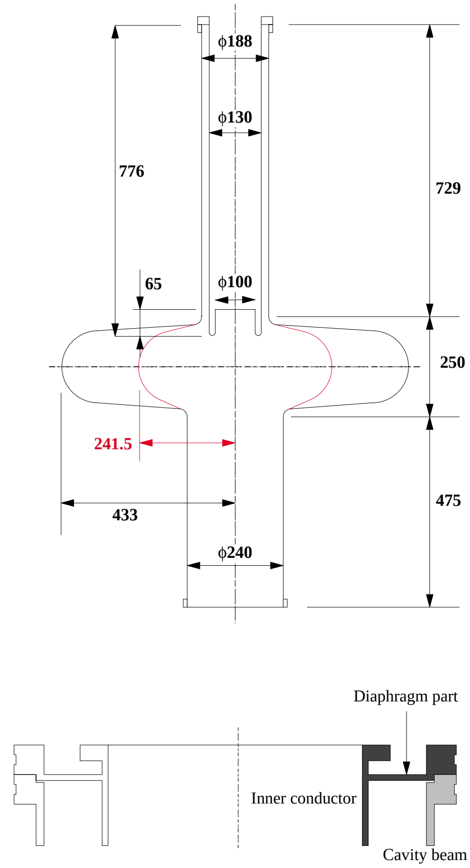

Figure 2: Simplified inner conductor attached to the cavity. Red line represents the cavity cell of short axis.

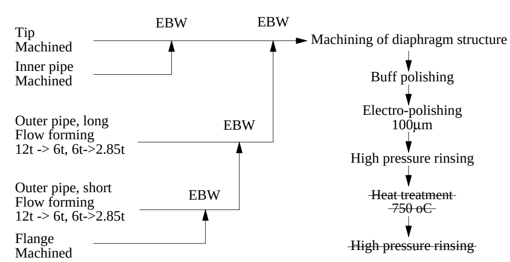

Figure 3: Fabrication flow and surface treatments of the simplified inner conductor.

the same as for the cavity, but we skipped heat treatment because of financial costs. Fig 3 shows a flow chart of fabrication and surface treatments.

4 VERTICAL COLD TEST

4.1 Q-degradation

We installed the inner conductor into cavity in a clean room, then assembled it to a cryostat. We conducted several cold tests in a vertical cryostat. Fig. 4 shows test results from 1st to 5th cold tests. Q-values of the cavity with no conductor are plotted in the same figure for comparison. At the 1st cold test, Q-values degraded slightly at low fields and sharply decreased at high fields with X-ray radiation. This Q-slope with X-rays indicates that the cavity was contaminated by “air dust” particles. We cleaned the cavity and the inner conductor by the high-pressure ultra-pure water rinsing (HPR), then tried the 2nd cold test. We decreased cool-down speed to avoid vacuum leakage at indium seal. At the 2nd test, Q degraded significantly and the deflecting voltage (kick voltage) did not reach the required value. The inner conductor was polished by EP (5 μm) after the 2nd test. This is to clean up scratches we accidentally made during HPR. At the 3rd test, Q-values still degraded as shown in Fig. 4. We further decreased cool-down speed to avoid another vacuum leakage at indium seal. Q-values degraded significantly at the 4th and the 5th cold tests. Fig. 5 shows cool-down curves from 300K to 4.2K measured at the conductor flange. Q degraded with decreasing cool-down speed. This degradation is so-called “Hydrogen Q-disease”.

4.2 Calorimetric RF measurement

To identify the location of Q-degradation, we measured RF loss at the inner conductor. As shown in Fig. 6, the inner conductor can contain liquid helium. By measuring liquid helium consumption with a level meter, RF loss of the conductor can be obtained. The loss measurement was calibrated using a heater set at the bottom of the inner conductor. We measured RF loss of the conductor at several RF fields. As an example, liquid helium level at

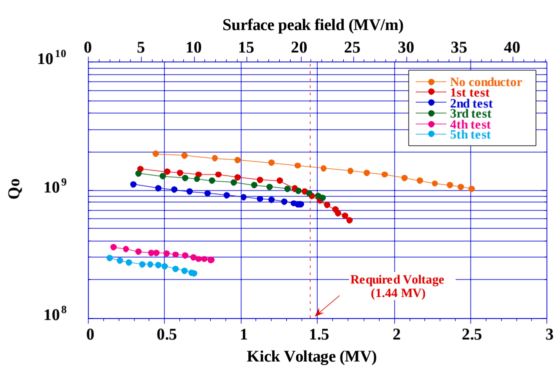

Figure 4: Cold test results.

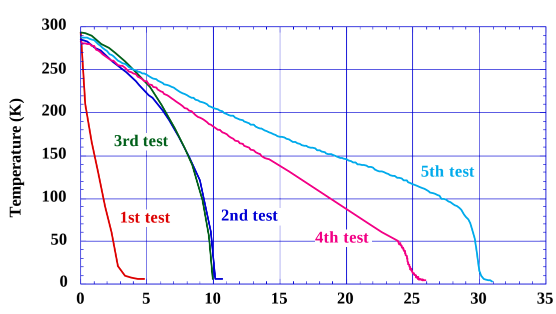

Figure 5: Cool-down curves.

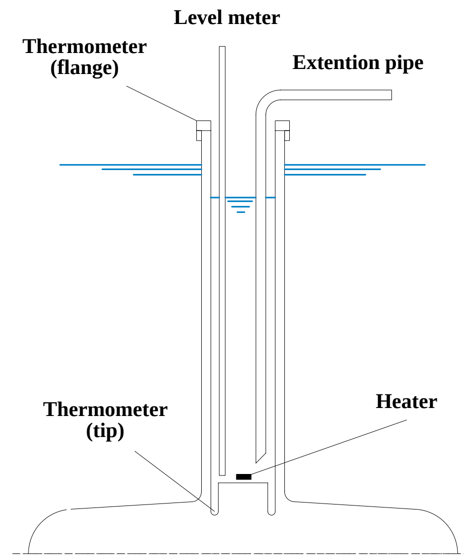

Figure 6: Setup for calorimetric measurement.

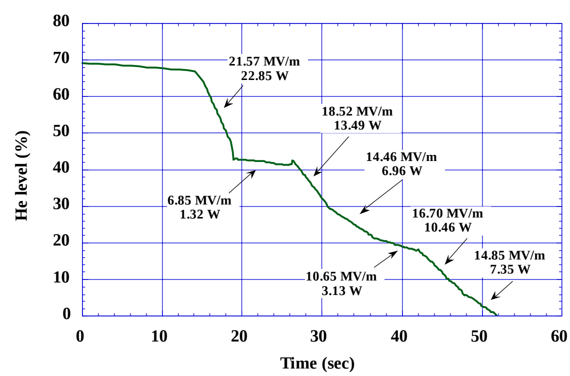

Figure 7: Liquid helium level and conductor losses at several fields.

several RF fields is shown in Fig. 7. The total RF loss was obtained form RF power measurement. Ratio of the conductor loss to total loss was about 40% at the 3rd test and 90% at the 5th test. The conductor loss is a cause of the Q-degradation.

4.3 Warm-up and quick cool-down

By blowing gaseous helium from an extension pipe (Fig. 6) set in the conductor, we warmed up the inner conductor while the cavity was kept cold. To monitor temperatures, thermo-couples were set at the tip and flange of the conductor. After warm-up, temperature was kept above 200K for two hours. By feeding liquid helium through the extension pipe, the conductor was quickly cooled down. Fig. 8 shows warm-up and cool-down curves at the tip and flange. The cavity was tested after this procedure. The Q-values recovered as shown in Fig. 9 and we achieved the required voltage.

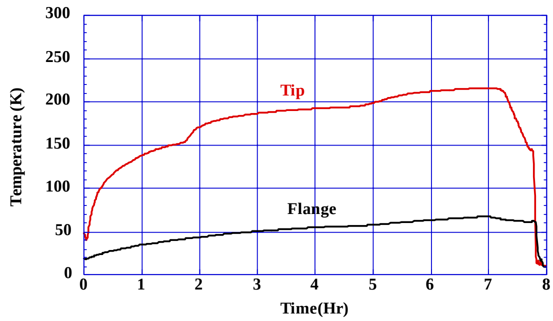

Figure 8: Warm-up and cool-down curves.

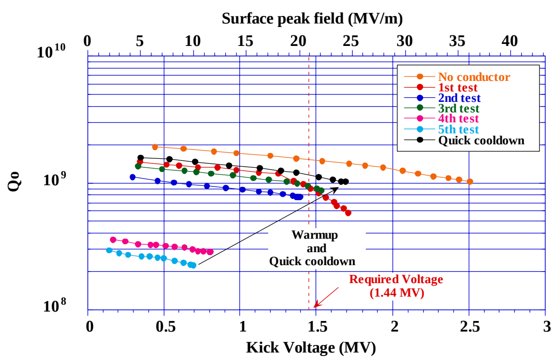

Figure 9: Recovery from Q-degradation.

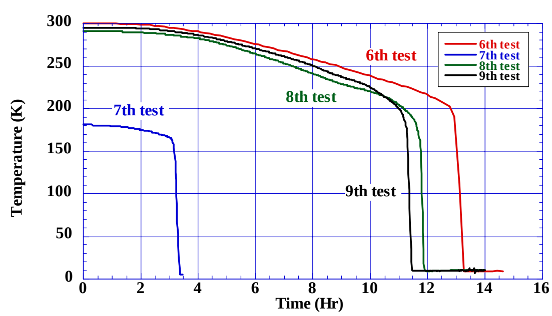

Figure 10: Cool-down curves from 6th to 9th cold tests.

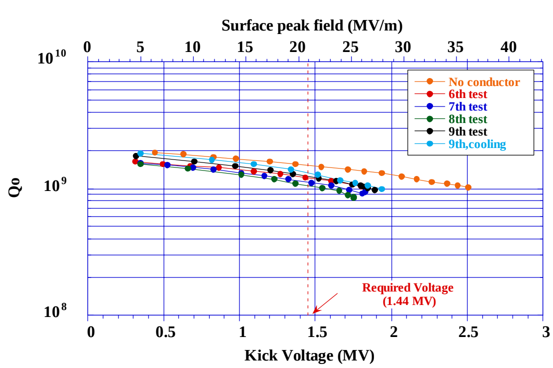

Figure 11: Cold test results from 6th to 9th tests.

4.4 Quick cool-down below 200 K

To avoid Q-degradation, quick cool-down is needed. However, vacuum leakage may happen during cool-down. Since the "hydrogen Q-disease" occurs when the cavity stays at temperatures between 125 to 80 K, we tried new cool-down scheme, such as slow coo-down (10K/H) and quick cool-down below 200 K. Fig. 10 shows cool-down curves from 6th to 9th cold tests. Temperature of the inner conductor was monitored by a thermo-couple set at the tip (Fig. 6). At the 7th test, the temperature of the conductor was kept at 180 K for about a half day. Fig. 11 shows test results. We observed no Q-degradation with this cool-down scheme.

4.5 Sub-cooling at the inner conductor

Although the Q-degradation was avoided by quick cool-down, the Q-values are still slightly low compared to that of cavity with no conductor. The RF loss of the inner conductor at required voltage is about 10 W at the 6th cold test, which are about 20% of the total RF loss. Calculation of the MAFIA shows that the ratio of the conductor loss to total loss is about 6%. Sub-cooling of the inner conductor may help to suppress the RF loss at the inner conductor. To test this possibility, we made a sub-cooler shown in Fig. 12. The cooler consists of a J-T valve, a vapour-liquid separator, which is thermally insulated by an outer vacuum vessel, a heat exchanger made of a copper pipe, and a vacuum pipe for pumping. We set the sub-cooler at the inner conductor as shown in Fig. 12. The cooling power is about 1W at 2.2 K. Sub-cooling the inner conductor, we measured Q-values at low fields (Esp=5 MV/m). The loss ratio can be estimated using an equation below,

$$\frac{Pcoax}{P} \approx 1 - \frac{Q}{Qcav}$$

where Pcoax is RF loss of inner conductor, P is total loss, and Qcav is Q-value of cavity with no conductor ($2\mathrm{x}10^9$ at Esp=5 MV/m).

At the 8th and 9th tests, we tried sub-cooling at the inner conductor. The loss ratio is plotted in Fig. 13 as a function of Tc/T, where Tc is the critical temperature of niobium (9.2K) and T a temperature at the tip of the conductor measured by a carbon-glass resistor. The 8th test showed that the loss ratio at 4.2 K (21 %) decreased quickly to 13 %. At the 9th test, the Q-value at 4.2 K is $1.8\mathrm{x}10^9$ and the loss ratio is around 9%. The conductor loss is still large at low temperatures.

Sub-cooling the conductor, we performed RF test at the 9th test. Results are shown in Fig. 11. Conductor temperature, which was 2.2K at low fields, increased to 4.2K by the conductor loss. The field limit slightly increased.

5 CONCLUTIONS

To develop a crab cavity for the KEKB accelerator, we have fabricated a prototype squashed cell cavity and a simplified inner conductor for a co-axial beam pipe coupler. The cavity with the inner conductor was cooled and tested in a vertical cryostat. Serious Q-degradation was observed during cold tests. This degradation is so called "hydrogen Q-disease". A calorimetric RF loss

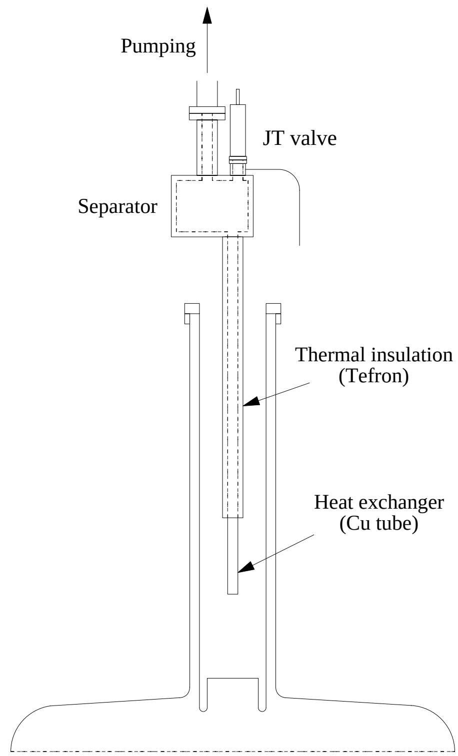

Figure 12: Sub-cooler set in the conductor.

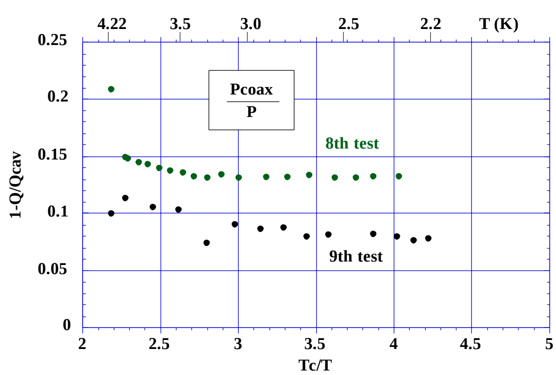

Figure 13: Conductor loss ratio.

measurement showed that the inner conductor is a cause of the Q-degradation. To avoid this degradation, we applied slow cool-down (10K/Hr from 300 K to 200 K) and quick cool-down (below 200 K). No Q-degradation was observed with this cooling procedure and we achieved a required deflecting voltage.

"Hydrogen Q-disease" was caused by hydrogen trapped in niobium. In our standard cavity treatments, the conductor is heat treated in at 750 °C. This heat treatment extracts hydrogen. This treatment was skipped from financial costs. The degradation occurred at the cold test, however, could be avoided by the quick cool-down procedure.

The Q-values are still low compared to that of the cavity with no conductor. To test a possibility to improve the RF performance, we have made a sub-cooler to cool the inner conductor. Sub-cooling did not significantly improve the RF performance. The conductor loss is still large at low temperatures. Heat treatment at 750 °C may improve the conductor loss.

Now, we are preparing for a horizontal cold test. A horizontal cryostat was designed already and a stub support, a notch filter, a co-axial input coupler, etc., are being constructed.

6 ACKNOWLEDGEMENTS

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