RECENT DEVELOPMENT OF HOM ABSORBERS FOR KEKB SUPERCONDUCTING CAVITIES

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Abstract

Beam tests of a superconducting cavity (SCC) module at TRISTAN Accumulation Ring showed that vacuum plays an important role on reducing trips. Since higher-order-mode (HOM) absorbers will be a major gas source during the operation, further reduction of outgassing rate was recommended. Here, we present an improvement of the outgassing rate by a longer baking. We reached a level where 3 months of operation at absorbed power of 8 kW without warm-up is possible. Another problem we encountered was cracks in the absorber that were found accidentally after the beam tests, although there was no symptom of degradation during the tests. We will present some results of investigation on cracks with acoustic tomography in detail and an improvement toward removal of cracks.

Introduction

Four single-cell SCC modules will be installed in the KEKB tunnel in the summer of 1998 [1]. Figure 1 shows a side view of one module. There, a few modification was made from the first design. They are to enlarge the diameter of end ducts from 100 mm to 150 mm and made the length of tapers longer in order to reduce loss factor.

One full-featured cavity module with HOM absorbers were tested in TRISTAN Accumulation Ring (AR) in 1996 and its feasibility was proved up to currents of 0.57 A. HOM absorbers absorbed maximum power of 4.2 kW in total and showed no problem during the tests. However, the following problems were seen as future problems, (1) outgassing rate of the absorbers should be reduced further to operate SCC's for a couple of months without warm-up and (2) cracks were found in the ferrite during an inspection with a microscope after the test, but whether it occurred during the beam tests was unclear since the absorbers had not been checked microscopically before beam tests.

In this paper, we present these problems in detail and describe how we are planning to solve them.

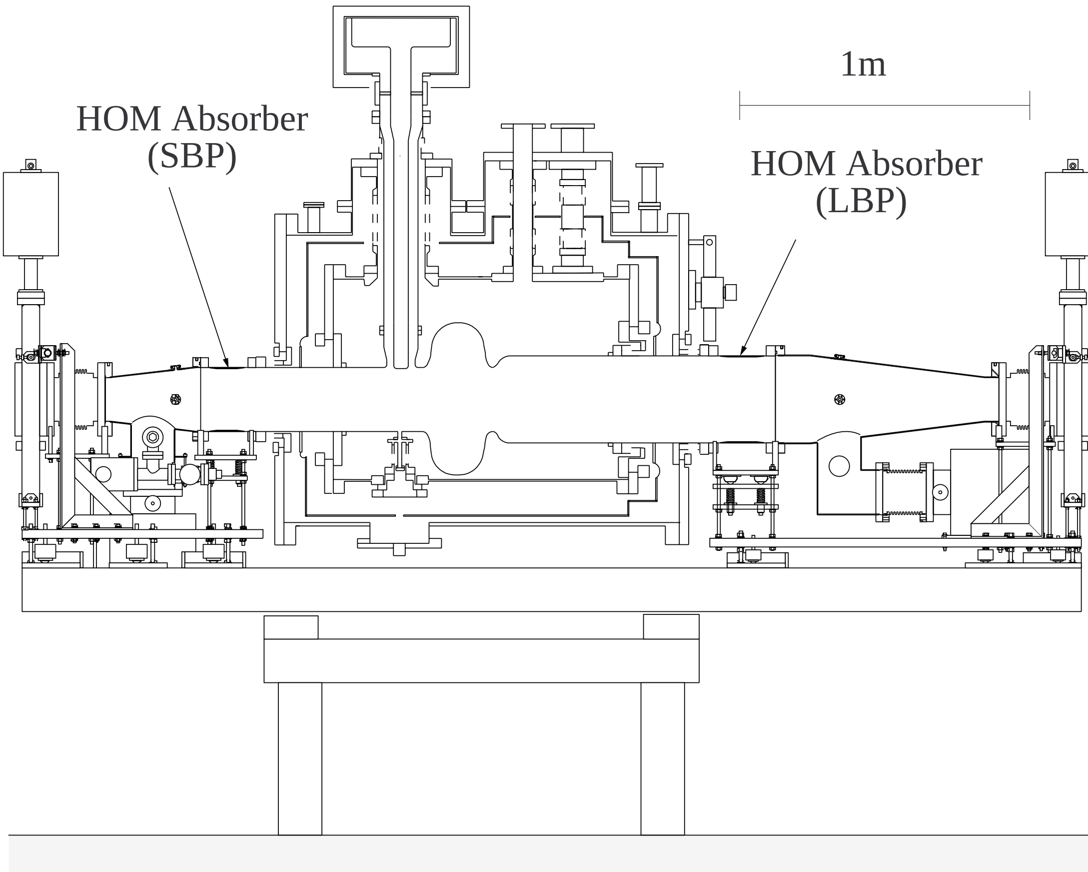


Figure 1 : Superconducting cavity module for KEKB.

Reduction of outgassing rate

Beam tests at TRISTAN AR showed that the gases condensed on parts of cavity such as input coupler cause trips and it is important to keep them as little as possible [2]. Though we could not get to the point when the outgas from HOM absorbers starts affecting the performance in the last beam test, in the previous tests where many trips occurred, the tolerable amount of condensed gases are roughly estimated to be 1 Torr liter. The main source of these gases will probably be the ones from HOM absorbers during operation with high currents due to the higher temperature. Figure 2 shows predicted average surface temperature as a function of absorbed power. It is predicted that the present level of outgassing rate is insufficient for 3 months of operation without warm up. Past experiences in baking suggested a possibility to further reduce outgassing rate by baking for a longer time [3]. Though high temperature can reduce the baking time in principle, unfortunately, in order not to cause cracks in ferrite, the baking temperature cannot be high. As will be shown later, it was found that a baking even at 150 °C can cause some cracks. However, since lower temperature baking requires more than one month of baking, we decided to look for some method to bake at 150 °C.

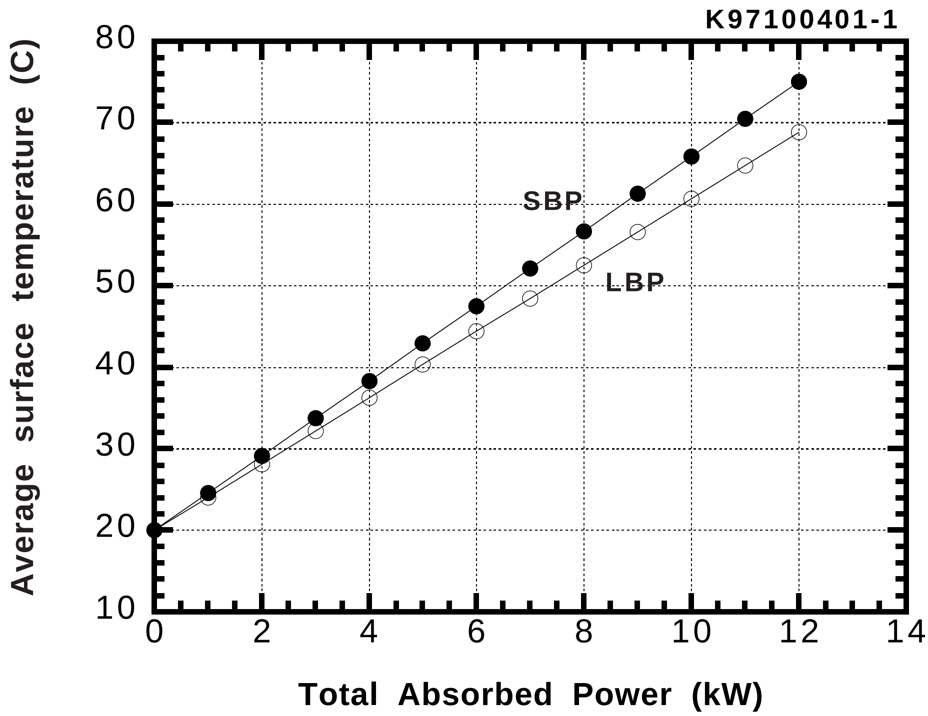


Figure 2 : Calculated average surface temperature of ferrite as a function of total absorbed power.

Assuming that we will bake the absorber at 150 °C, the outgassing rate was measured using the setup shown in Fig. 3. Figure 4 shows the outgassing rates of the absorbers that were baked at 150 °C for one month as a function of temperature, together with previously obtained best value for comparison. The outgassing rate was reduced by a factor of 3 to 4. Figure 5 shows predicted outgassing rates from SBP (small beam pipe at the upper stream) and LBP (large beam pipe at the upper stream), and their total as a function of total absorbed power. The expected total absorbed power in KEKB HER (high energy ring) is 6 to 8 kW, based on calculations with ABCI and measurements of absorbers. The total amount of condensed gases after 3 months of operation is shown as a function of total absorbed power in Fig. 6, together with the data on the absorber used for the previous beam tests. It shows that the amount of condensed gases will not reach the presumed trip level up to 8 kW. In other words, the absorbers should be baked at 150 °C for at least one month, which is not a difficult task. Also, in our past experiences, once it is baked, even if you have to expose it to air for re-assembly etc. , baking for about one day is enough to reach the outgassing level similar to that before exposure to air.

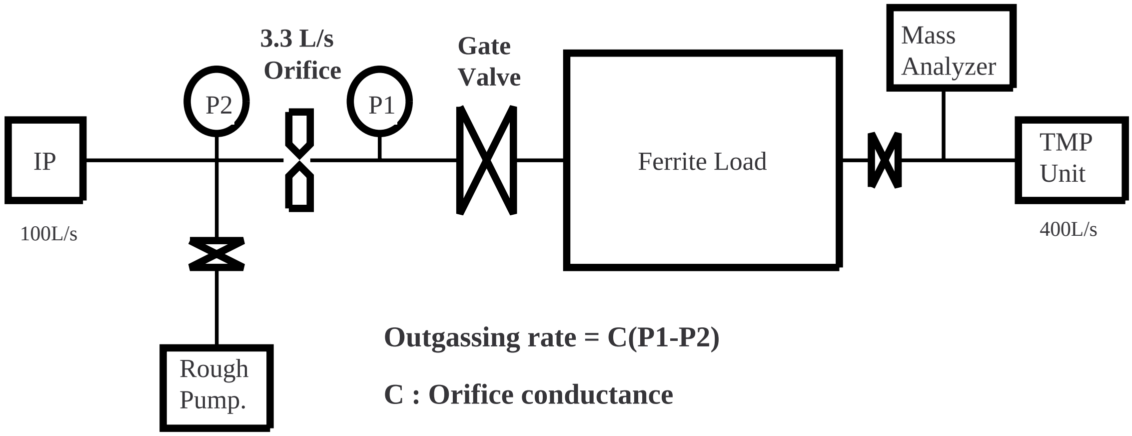


Figure 3 : Schematic of outgas measurement setup.

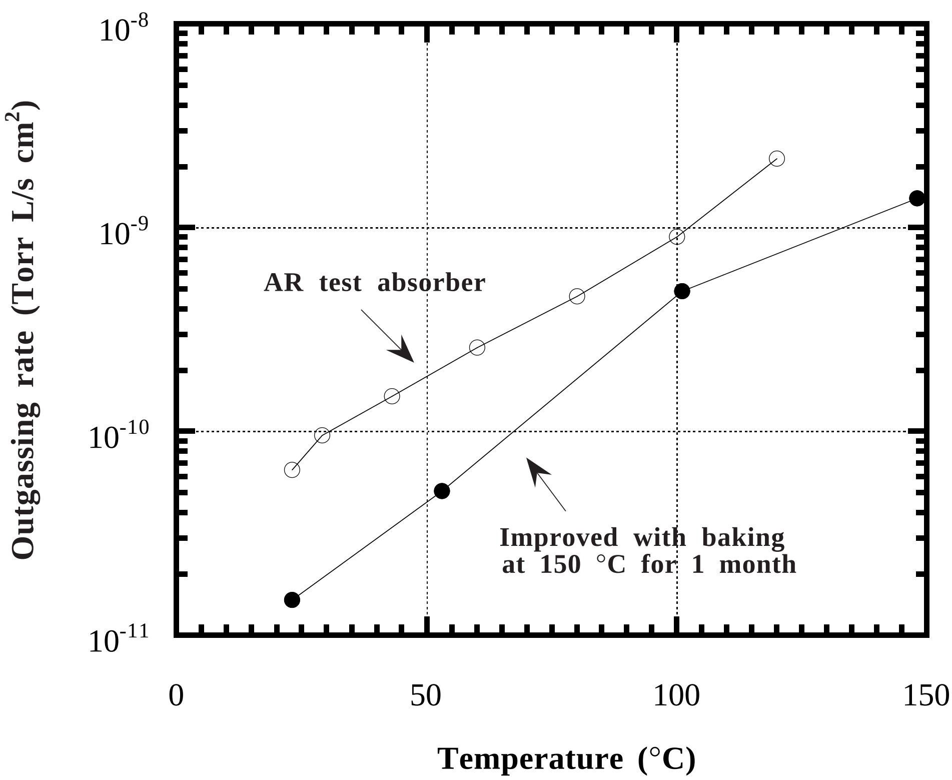


Figure 4 : Outgassing rate as a function of temperature. Reduction of outgassing rate with further baking can be seen.

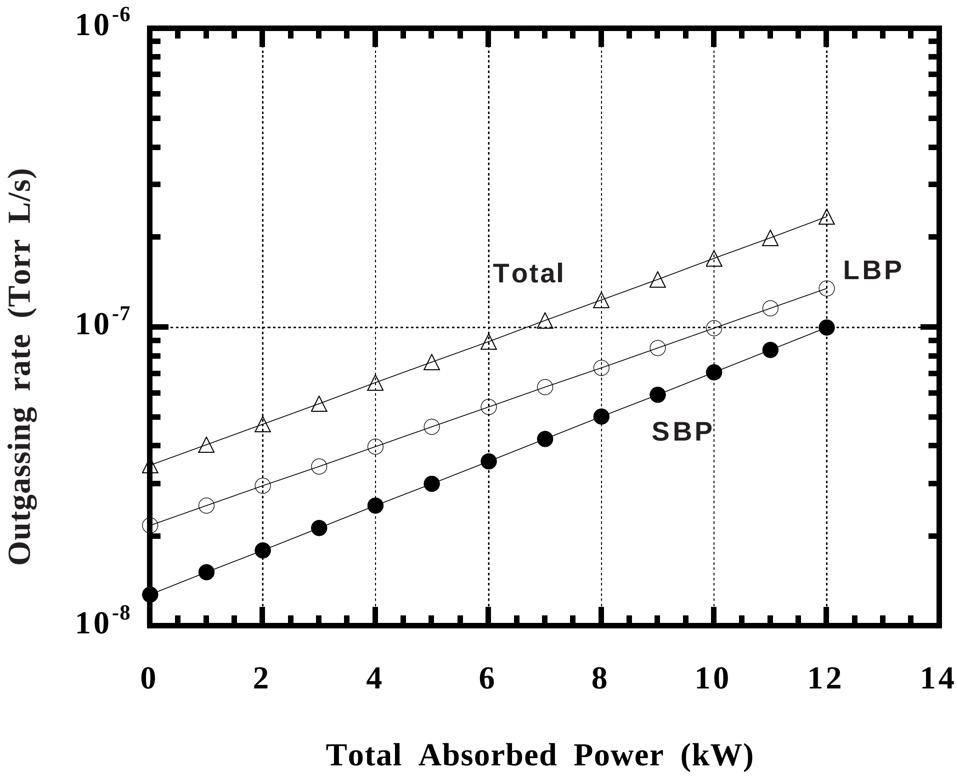


Figure 5 : Calculated outgassing rate as a function of total absorbed power using experimental data.

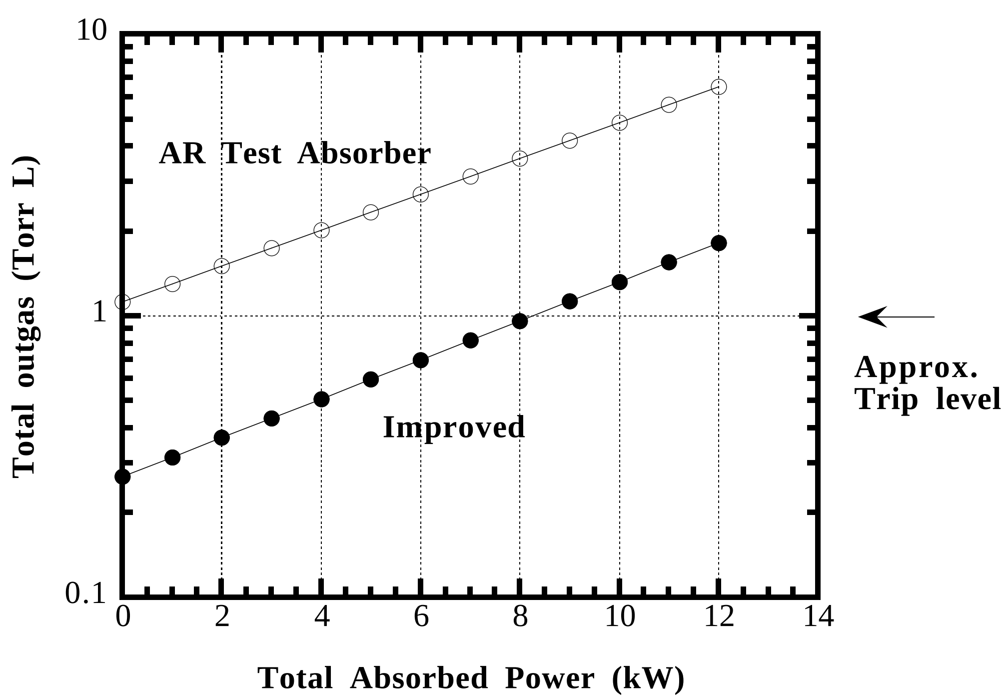


Figure 6 : Total amount of gas after 3 months of operation as a function of total absorbed power.

Cracks and its remedy

As mentioned earlier, some cracks were found by accident while we were inspecting the ferrite surface of one beam-tested HOM absorber with a probe microscope. That was our first time to use a microscope. We checked absorbers only with our eyes before since the area is so large for an inspection with a microscope that we did not try. However, now that some cracks were found, we decided to check the absorbers with some method that has better sensitivity and resolution than human eyes and relatively faster than optical inspection because thorough optical inspection takes a few days per absorber and we had no time and man power for that. We tried acoustic inspection, magnetic inspection and color check. Fortunately, Hitachi, Inc. kindly offered their machine for acoustic inspection and it turned out to be the best way to find cracks and delaminations in the ferrite among the three. Therefore, we decided to use acoustic inspection or so-called acoustic tomography most of the time.

Acoustic tomography

Sound waves propagate through solids, liquids and gases. For inspections of welds or defects, ultrasonic waves of a few MHz are normally used today since the space resolution is about a half of wave length. We have been using pulse echo method, i.e. ultrasonic pulses are sent to a material in a medium and analyze their echoes. When the wave pulses hit a material, part of the waves bounces back and part of them propagates in the material. The reflection coefficient of ultrasound waves, when they go through medium 1 and hit a material 2, is described as follows.

$$r = \frac{P_r}{P_f} = \frac{Z_2 - Z_1}{Z_1 + Z_2} \quad , \tag{1}$$

where P is the sound pressure and Z the acoustic impedance or a product of density and sound speed in the corresponding medium or material. “f” and “r” designate forward and reflected, respectively.

Acoustic tomography is the technology that visualize the variation of the pressure of the sound waves that are reflected from the points of interest.

Measurement procedure

We first set a HOM absorber on a rotatable table in water as a medium for sound wave to propagate. Then we set a transducer (transmitter/receiver) that is concave so the waves can converge on the surface of interest. Figure 7 schematically shows the propagation of ultrasonic waves in case of surface and boundary inspections. A picture of the whole set-up is shown in Fig. 8. The subsequent procedure is as follows.

(1) Set the distance between ferrite surface and the sensor to be about 1 inch (focal length).
(2) Looking at the sound pressure reflected from the surface on an oscilloscope, the position and angle of the transducer are adjusted so that the pressure becomes the strongest.
(3) Move the transducer to the center of the area to be scanned and input the size of the region to be scanned and increment of the steps of data taking. In azimuthal direction, we normally scan 40 deg. and 60 deg. for SBP and LBP, respectively, at one time . In axial direction, we scan the whole length at one time. Data are taken every 0.08 degrees and 0.12 degrees in azimuthal direction and 0.24 mm and 0.30 mm in axial direction, for SBP and LBP, respectively.
(4) Start scanning. Scanning is performed by moving the transducer in axial direction and rotating the absorber clockwise and counter clockwise. When a series of scanning is finished, the absorber moves back to the starting position automatically.
(5) Make a file and store the scanned data into it, then rotate the absorber 40 deg. for SBP or 60 deg. for LBP manually.
(6) Repeat (4) and (5) till 360 degrees are covered.
(7) Monitoring the oscilloscope, move the transducer toward ferrite so that the sound waves focus on the boundary of copper and ferrite, i.e. the echo pressure of the waves that come back from the boundary gets strongest on the monitor, as shown at the bottom of Fig. 7.
(8) Repeat (4) to (6).
(9) The obtained images are stored as TIFF images and put together as an unfolded image of the whole surface as shown in Figs. 10 to 13.

It takes about 5 minutes for each scanning, i.e. 40 deg. and 60 deg. in azimuthal direction, for SBP and LBP, respectively. It takes about 3 hours to get both surface and boundary echo and to transfer data to floppy disks for one absorber. This is much faster than optical inspection and one can get maps of defects so that they can be compared with a new one at a later time whenever it is necessary.

It was fortunate that we were able to find an appropriate ultrasonic transducer that has an ideal focal length for the inspection of our absorbers.

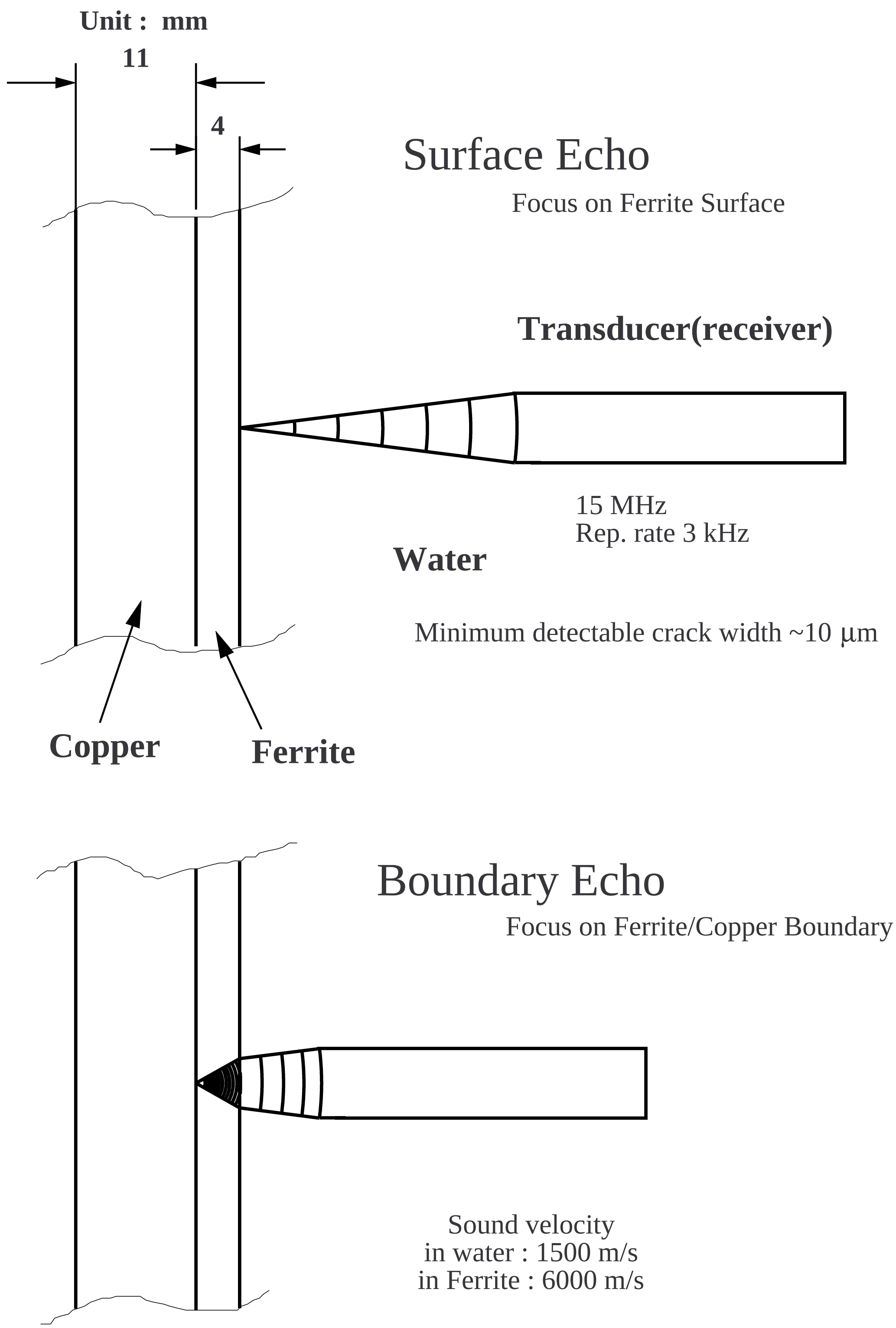


Figure 7 : Schematic of acoustic tomography. Measurements of the echo from the ferrite surface and that from the boundary between ferrite and copper.

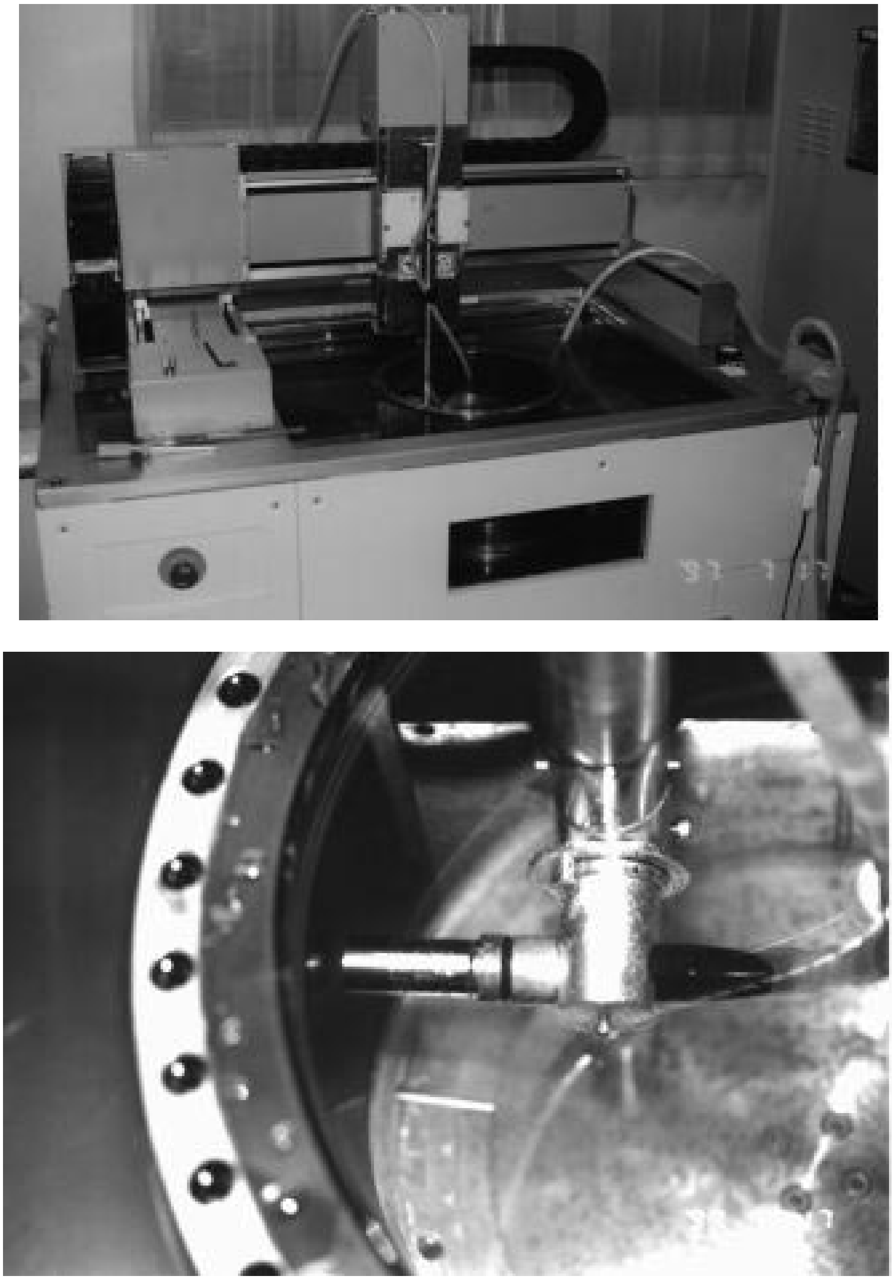


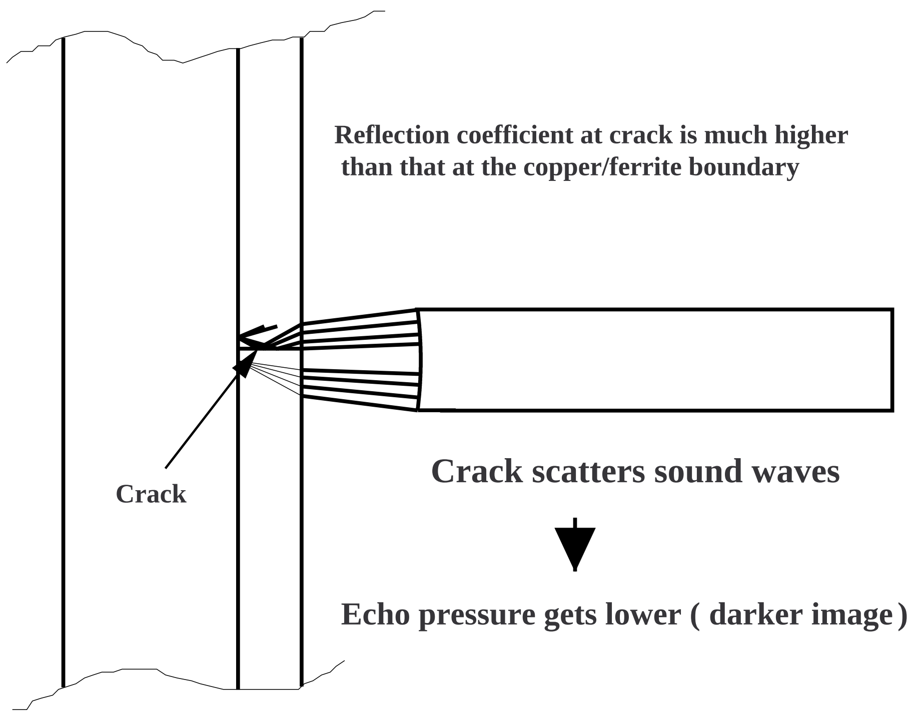
Figure 8 : Apparatus for acoustic tomography when a HOM absorber is being measured.

Principle of crack detection

Since cracks usually include air or water inside during the inspection, the reflection coefficient of sound waves at the cracks are so high (~95%) that almost all waves reflect at cracks as shown in Fig. 9. Also, if the crack is normal to the surface, the reflected waves do not go back to the transducer.

As a result, the sound pressure of the waves that return to the transducer (receiver) gets lower than that from the places where there is no crack. Therefore, the image of cracks is seen as broad dark lines in many cases. On the contrary, if the waves reflected from cracks go back to the transducer, it can be seen as brighter images. It happens if there are delaminations.

If a crack is normal to the surface,



If a crack is in parallel with the surface, i.e. delamination,

The reflected sound waves go back to the receiver and its pressure gets higher than that of the waves reflected from the ferrite/copper boundary because of higher reflection coefficient at crack or delamination

↓

Brighter Image

Figure 9 : Principle of crack detection.

Study on the cause of cracks and its prevention

Figure 10 shows the cracks found in the absorber that was tested in TRISTAN AR. The horizontal and vertical direction of the image shows azimuthal and axial directions, respectively. Also, the top and bottom dark bands are the echo images from tapers. In the image of surface echo, no cracks are seen. The bright vertical lines are not defects but the gaps of scanned images. As mentioned earlier, each scanned image covers 40 deg. and 60 deg. for SBP and LBP, respectively. Though each image can be put together seamlessly in many cases, the gaps can be seen occasionally as in Fig. 10.

Since the widths of the cracks were mostly less than 10 μm, i.e. narrower than the resolution of the machine, they were not detected by the surface echo, but as one can see in the bottom figure, they were detected very clearly by the boundary echo due to the enhancement with the scattering of the sound waves at cracks.

It was also confirmed, with color check that has spacial resolution of 1 μm, that most of these cracks open at the surface of ferrite. The image obtailed with color check showed a pattern very similar to the bottom image of Fig. 10.

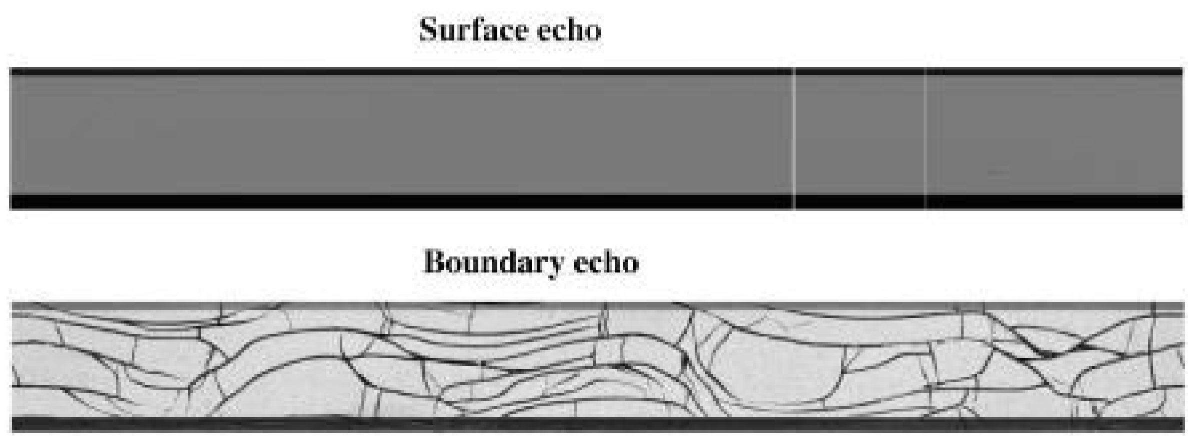


Figure 10 : Images of echoes from ferrite surface and copper/ferrite boundary. This absorber (#6S3) was used for beam tests in TRISTAN AR. Cracks are clearly seen in the boundary echo. Widths of cracks were less than 10 μm and too narrow to be detected by the surface echo.

In order to investigate on the cause of cracks, at first, we tested a couple of absorbers with acoustic tomography and it was found that there are no cracks when all the manufacturing process has finished, however, cracks were found in the absorbers that had undergone baking and high power test with microwaves. That suggested us to check if cracks occur during baking and high power test. At first, we tested baking as follows.

Figure 11 shows the echo images before and after baking at 150 °C. As one can see in the bottom picture of Fig. 11(b), many brighter lines appeared, which implies that cracks started at the ferrite/copper boundary. The reason why the lines are bright might be that the depths of the cracks are not deep enough to scatter the sound waves.

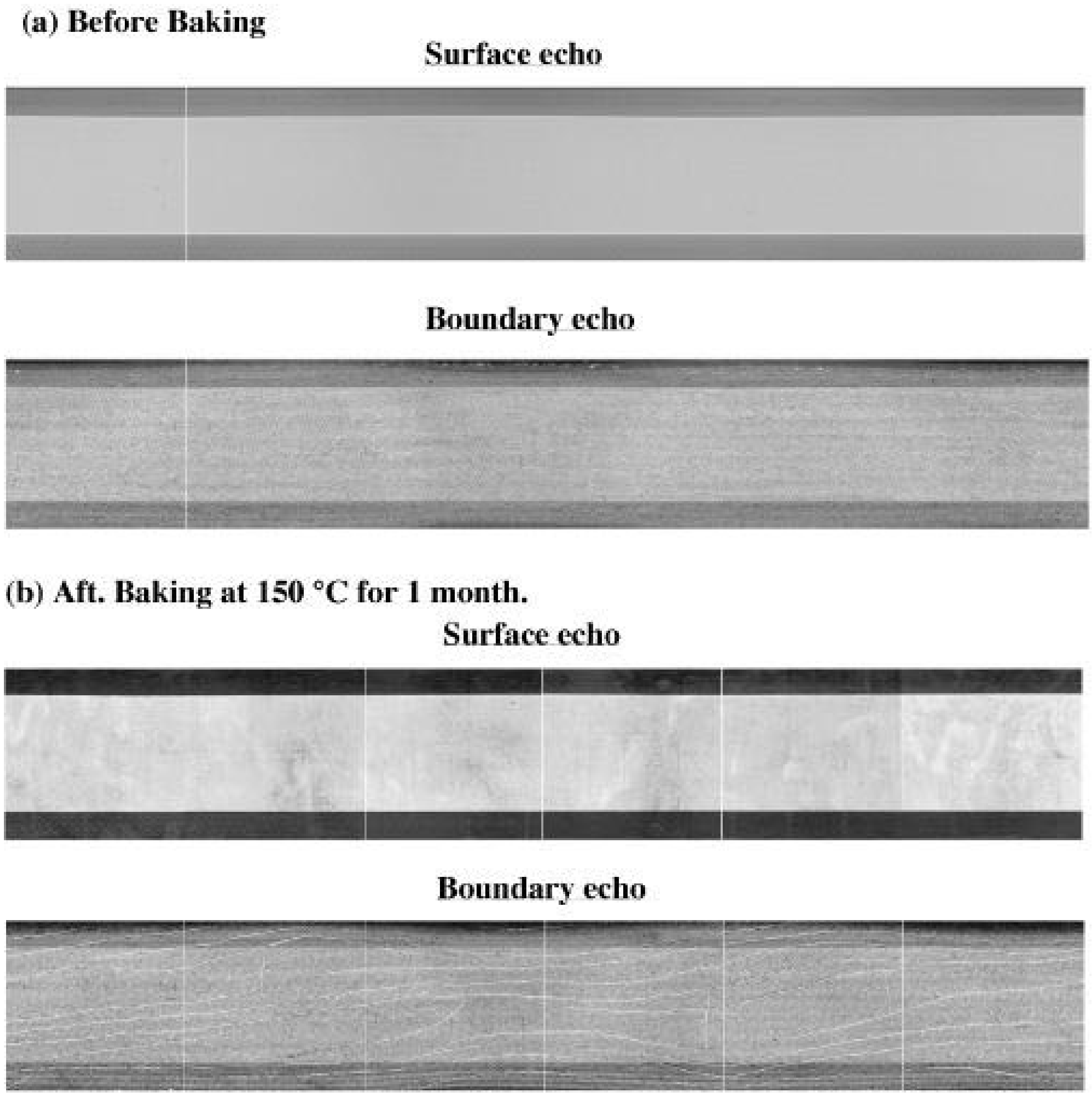


Figure 11 : (a) Echo images of the absorber before baking (#7LA). (b) After baking at 150 °C for 1 month.

The absorber baked at 110 °C also showed cracks as shown in Fig. 12, although the number of cracks were much less than that in Fig. 11b. Thus it was confirmed that baking causes cracks. Actually, long time before, we had heard some sounds that make one think of cracks while baking absorbers, but due to our poor inspection with only bare eyes, we could not find cracks.

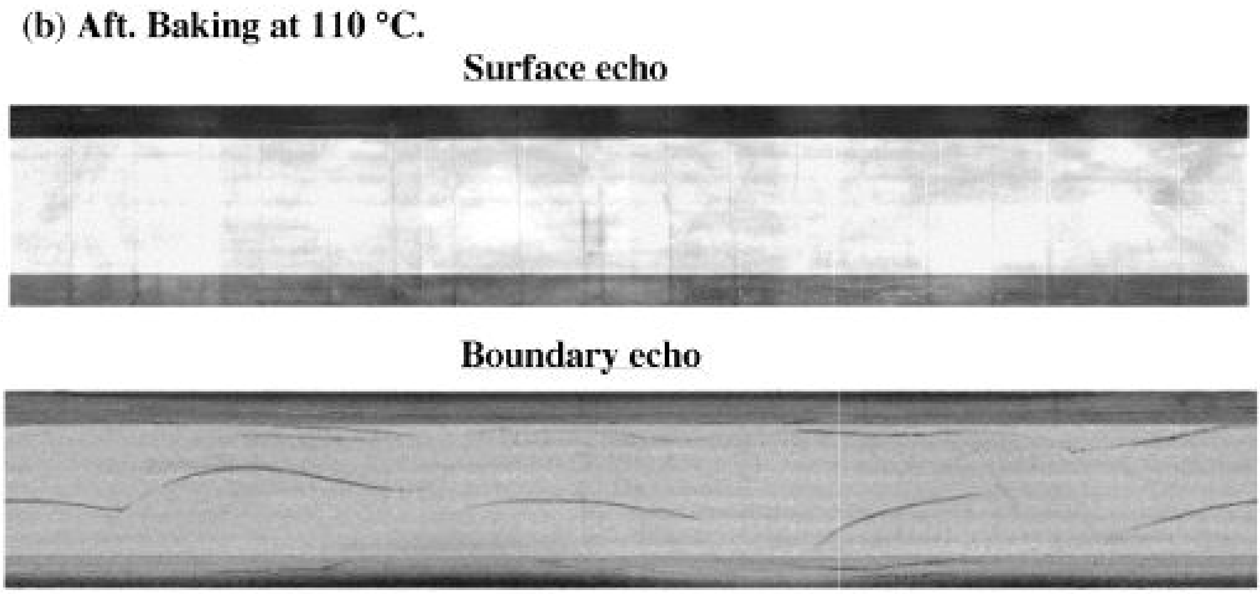


Figure 12 : Another absorber after being baked at 110 °C (#7LB).

Taking into account that the thermal expansion coefficients of copper and ferrite are 18×10^{-6} and 8.5×10^{-6}, respectively, we assumed that the expanding force of copper surpasses the breaking strength of ferrite and thought of how to reduce the expansion of copper relative toferrite. At first, baking of ferrite from inside using infrared light or microwave while cooling outside with water was considered. However, since instrumentation for this is costly and difficult to bake after installing absorbers in the beam line, we decided to try the following idea. In the process of manufacturing, copper layer is covered with another layer of 11 mm-thick soft steel [4]. Though we normally remove this layer after HIP, considering that the expansion coefficient of this soft steel is 11×10^{-6} and it is firmly bonded to copper with HIP, leaving this layer might help reducing the expansion of copper. Thus, using an absorber with soft steel layer left, we baked and checked if cracks occur. No cracks occurred after baking at 150 °C. Then, we reduced the thickness of soft steel to 3 mm so the configuration of cooling pipe can be similar to the previous one with a larger diameter water cooling pipe (1/2 inches). Consequently, as shown in Fig. 13, no cracks appeared and it was confirmed that leaving the soft steel layer is effective to prevent cracks. At this moment, the final test with the cooling channel has not been done yet and there are chances of cracks due to the loss of soft steel to make the cooling channel.

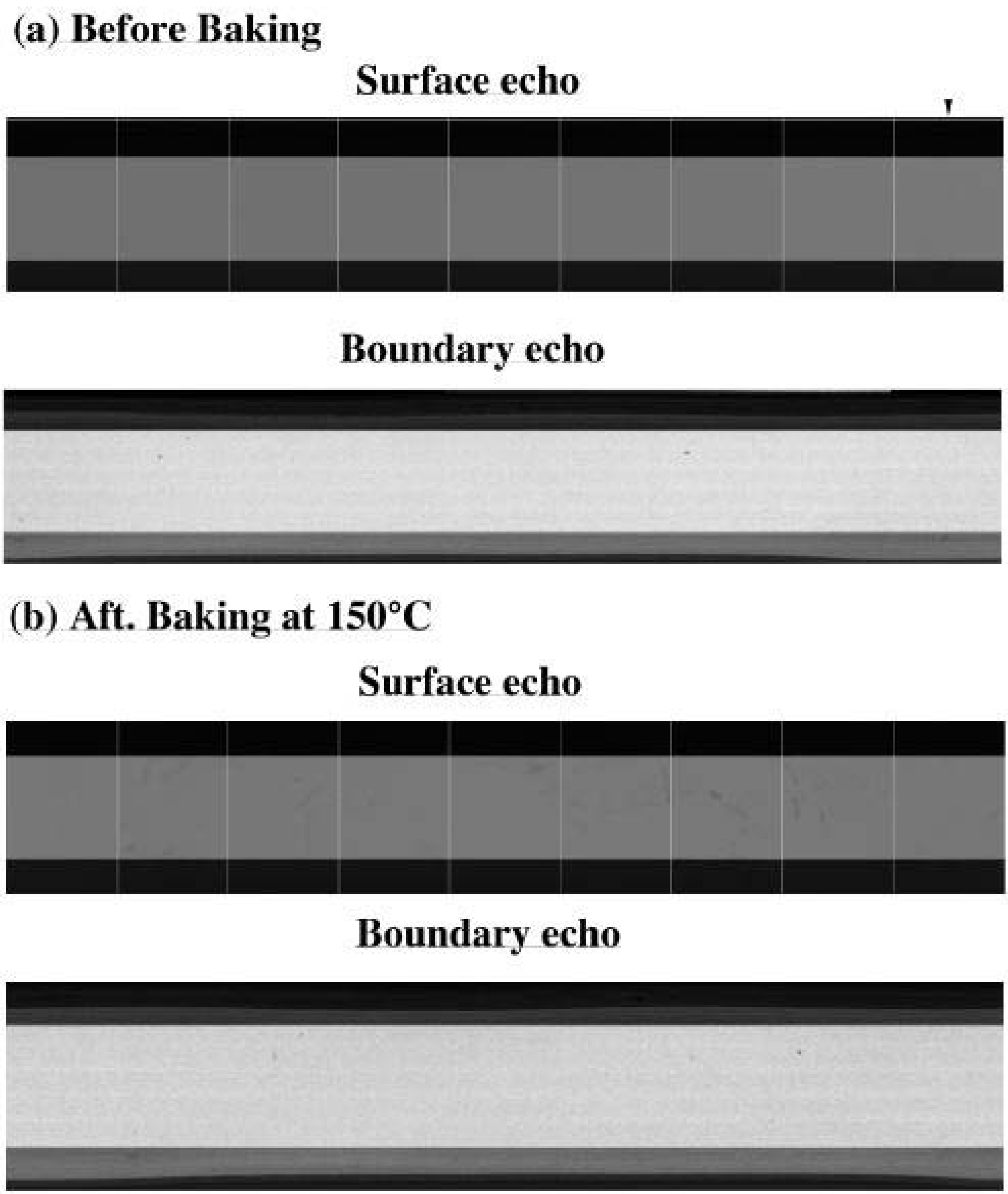


Figure 13 : (a) Echo images of the absorber with 3 mm-thick soft steel layer over copper before baking (#11S2). (b) After baking at 150 °C.

Figure 14 shows a modified design of SBP with 3 mm-thick soft steel layer on copper with a 1/2-inch cooling pipe that is press-inserted in the channel.

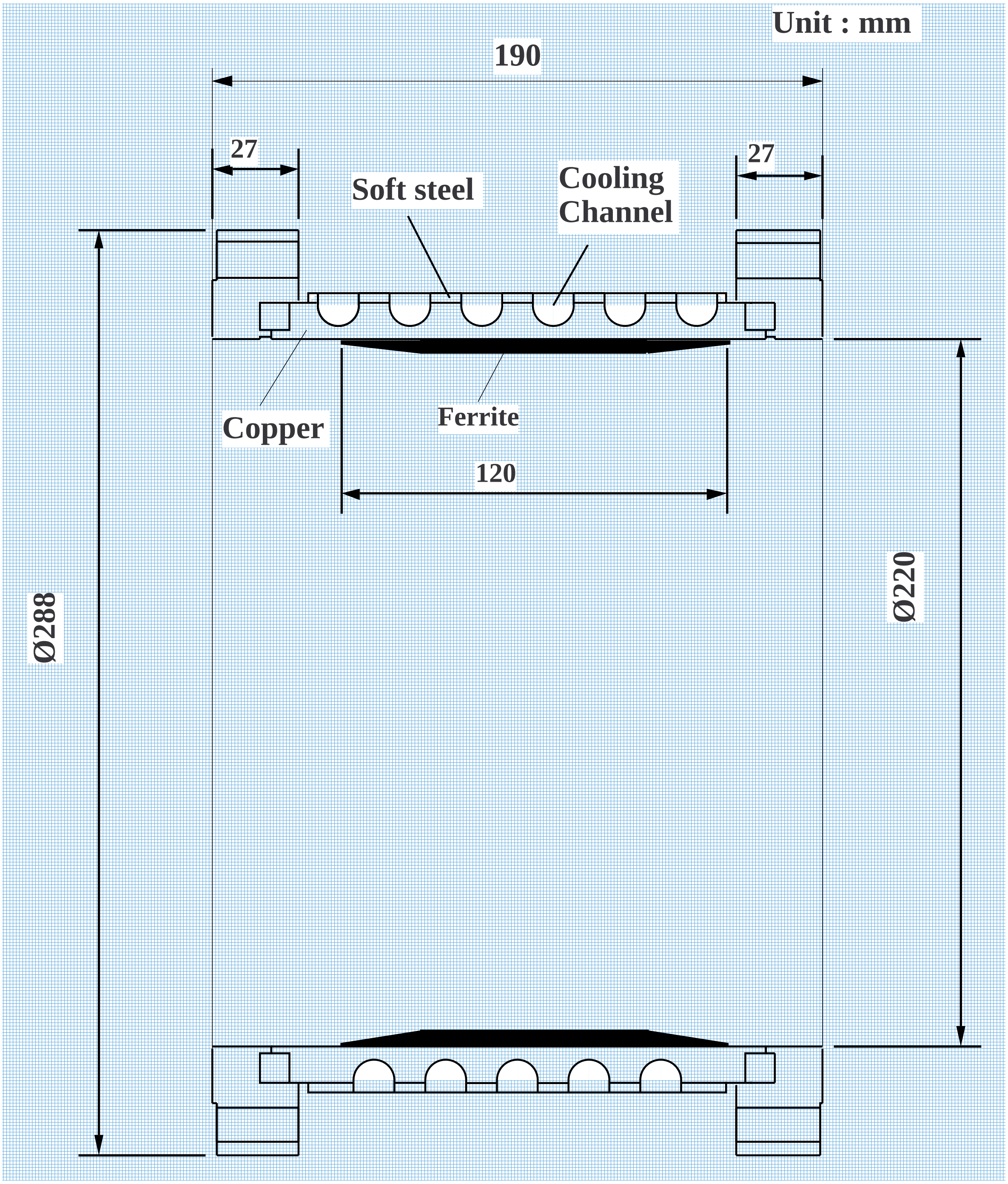


Figure 14 : Modified design of the absorber (Small Beam Pipe). The ferrite thickness is 4 mm with 25 mm long tapers at both ends. 3 mm-thick soft steel layer is left on copper.

High Power Test with 508 MHz coaxial line

Using 508 Mhz coaxial line, up to 5 kW and 7 kW of absorbed power for SBP and LBP, respectively, was tested and no cracks occurred. This power is about twice as much as we expect at KEKB HER.

Conclusion

Outgassing rate of the ferrite absorber was reduced to a practical level, i.e. 3 months operation at 8 kW without warm-up, by baking at 150 °C for one month.

Investigation on cracks and their sources is underway. To date, it was found that baking causes cracks due to the difference of thermal expansion coefficients of copper and ferrite. Considering that the soft steel layer, that is normally removed after HIPping, has a thermal expansion coefficient closer to ferrite, we tried to leave this layer to reduce the expansion of copper. No cracks occurred after 150 °C baking with 3 mm-thick soft steel layer and confirmed its effectiveness, although there was no cooling channel yet. Since there are parts where soft steel layer have to be removed to make cooling channel, there are still chances to have cracks. We hope to find a solution to solve the problem as soon as possible.

Also, the limitation of the usage of the dampers that have cracks will be investigated with high power tests using 508 MHz coaxial line.

References

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[3] T.Tajima et al., Proc. 5th European Particle Accelerator Conference (EPAC96), p. 2127 (1996).
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