DESIGN STUDY OF A TEST CAVITY FOR EVALUATING RF CRITICAL-MAGNETIC FIELD OF THIN-FILM SUPERCONDUCTOR*

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Abstract

In the second stage of ILC, a superconducting cavity with high gradient of more than 45MV/m is required. To obtain such a high gradient, there has been proposed a method of increasing an RF critical magnetic field of the cavity inner surface by coating multi-layer thin-film superconductor, which their thickness is close to the London penetration depth. By producing a multi-layer thin-film structure in cavity inner surface, it is thought to improve the RF critical magnetic field, and to connect directly to high gradient.

In order to demonstrate an RF critical magnetic field of a thin-film on a surface of Nb, an RF cavity with thin-film coated Nb sample is necessary to measure an RF critical magnetic field below critical temperature of a sample. Also it is necessary to design such a cavity producing strong RF magnetic field parallel to the sample thin-film surface. We have designed a mushroom-shaped cavity for that purpose and fabricated an aluminum model cavity.

In parallel, RRR measurement system was developed to evaluate thin-films.

MULTI-LAYER THIN-FILM SUPECONDUCTOR

A superconducting thin-film for a high electric field of an accelerator cavity application was proposed by Gurevitch 2006 [1]. The study of multi-layer thin-film superconductor is being on a way in many laboratories [2, 3, 4]. In order to achieve high acceleration gradients for the superconducting cavity of the second stage ILC accelerator, we started the study to evaluate a critical magnetic field of superconducting thin-films such as Nb_3Sn and NbN and MgB_2 deposited on the Nb samples. We chose an atomic layer deposition (ALD) method of film formation, which has an advantage of uniform and nm controllablity for thickness on a complex inner-surface structure of cavity. In order to develop application method of ALD on Nb surface, we need to measure lower critical field at a frequency of several kHz using a small coil, a superheating critical magnetic field of RF frequency using RF cavity respectively, as well as RRR for thin-film on a sample. There is theoretical study to evaluate a thickness of each layer for the best performance of multi-layer thin-film superconductor. We have shown that there is an optimum thickness of formed thin layer to get maximum superheating critical magnetic field [5]. Those are the target structure in this study.

DESIGN AND MANUFACTURE OF THE ALUMINUM MUSHROOM-SHAPED CAVITY

Calculation of Electromagnetic Field in the Cavity

A mushroom-shaped cavity has a shape of half hemisphere with flat bottom plate. It has an advantage to make strong magnetic field closing well inside of the cavity and facing to the sample surface of the bottom plate, on the other hand, a magnetic field on the hemisphere surface can be reduced compare to the bottom surface. The resonant frequency of the cavity was selected to 3.9 GHz to make it compact as possible. It corresponds to a triple harmonics of 1.3 GHz which is the resonant frequency of the superconducting accelerating cavity of ILC. The shape of the cavity was based on the mushroom-shaped cavity of the SLAC study [6]. The stored RF power is limited by thermal superconductivity destruction of Nb of the cavity. We have designed a cavity so that the magnetic field of the sample surface to the magnetic field of the inner hemisphere wall holds a value twice or more. The electric field in the cavity inner wall has been designed to have minimum, in order not to generate field emission. A cylinder shape port at the top of the mushroom-shaped cavity is a coupled waveguide to put RF power into the cavity. The port is also used for a vacuum pumping port installation. CST MW STUDIO was used to design the cavity. By starting from the shape of SLAC cavity, a model dimensions were optimized to have 3.9 GHz with similar electric field and magnetic field inside. Then a shape of a bottom plate was modified to have strong magnetic field on the sample surface with weak magnetic field on the hemisphere surface. The bottom plate was extruded into the cavity, finally. Figure 1 shows final cavity shape and calculated electromagnetic field of inner surface in the cavity.

From the calculation, maximum excited magnetic field on the bottom sample surface is 51460 A/m, on the other hand, along the inner surface of hemisphere, the maximum excited magnetic field is 20409 A/m. As a result, the

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ratio of the sample magnetic field to the hemisphere magnetic field exceed 2, which is our target mode.

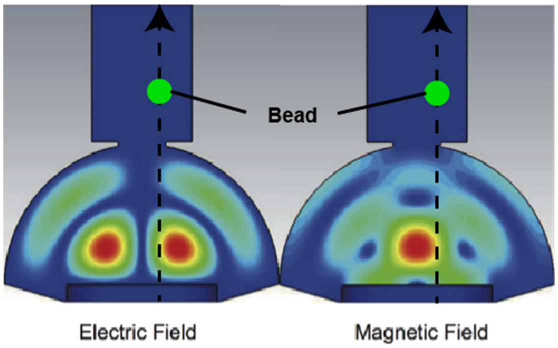

Figure 1: Electric and Magnetic field in mushroom-shaped cavity. The bead-pull paths are shown by dashed lines.

Manufacturing and Evaluation of Test Cavity

According to the simulation result, a test cavity was designed and fabricated by an aluminum to check whether electromagnetic field in the cavity has a calculated field or not. Figure 2 is the cross-sectional drawing of the test cavity. The radius of the hemisphere is 108.6 mm, and the height from the sample surface to top plate is 216.57 mm.

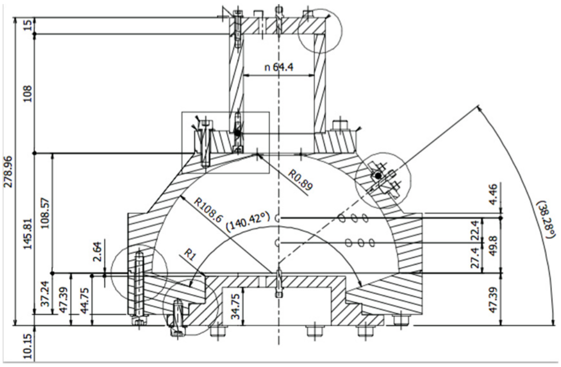

Figure 2: Cross-sectional drawing of mushroom-shaped aluminum test cavity.

They are divided by 6 parts, and are connected by bolts and taps. The border edge of the parts are machined to have small step, in order to touch each other rigidly at the edge for good electrical conductance. They also have holes for antennas and bead-pull through holes in the top and bottom plate, and in the hemisphere part.

At first, we should find a target mode of the aluminum test cavity. Various type of antennas were tested to excite and to detect the target mode. One of result is shown in figure 3. The red lines show the calculated resonant frequencies. The blue lines are the measured resonance frequencies. The number of resonance and their intervals were different. They were deeply affected by an exciter antenna position and a shape of antenna. The resonant frequency of the calculated target mode was at 3.924 GHz. For the corresponding measured resonant frequency, we took the mostclosest one, 3.927GHz mode as the target mode.

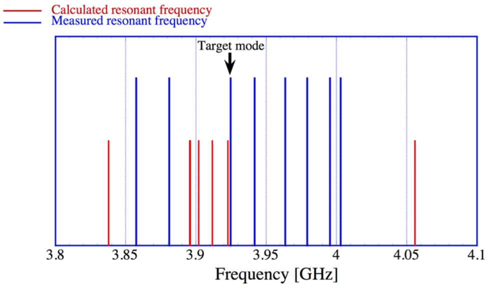

Figure 3: Distribution of resonant frequency for the calculation and measurement.

In order to confirm the field distribution of the target mode, bead-pull measurement was performed along parallel lines to the cavity longitudinal axis, as shown in doted lines in figure 1. The perturbation bead was aluminum ball with 5mm diameter. The shifts of a resonance frequency by the bead perturbation at the 3.927 GHz were measured and shown by the blue squares in figure 4. The red crosses in figure 4 were the calculated $\mu H^2 - \varepsilon E^2$ along the bead path with arbitrary scale factor multiplied.

In the calculation, magnetic field along the bead-pull path is dominated with maximum at the 30 mm above the sample surface. However, for the measurement, there is a strong magnetic field in the vicinity of the bottom sample surface, and the electric field become dominant in the cavity hemispherical center portion. The bead-pull measurements in other mode showed completely different magnetic field distribution from the target mode. The reason why the field distribution along the bead-pull path are different is under study. It may be a problem of these exciter antennas shape, which is considered that no excitation of target mode. The study is going on for antenna improvement. In addition, there is a need of separate measurement for the electric field and the magnetic field in the bead-pull by using ceramic bead, etc.

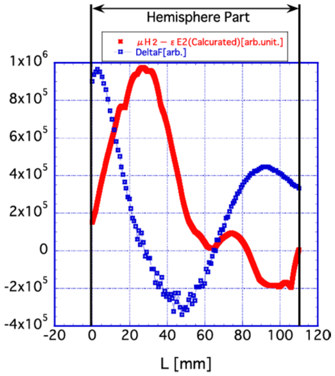

Figure 4: Comparison of bead-pull frequency shift between bead-pull measurement and CST calculation, at 3.927GHz mode. Red crosses are the calculation, blue squares are the measurement. L=0 is the bottom plate surface.

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CONSTRUCTION OF RRR MEASUREMENT SYSTEM

To evaluate a purity of the thin-film superconductors is important for the production of the multi-layer thin-film superconductors. A purity of material can be evaluated by a thermal conductivity. When impurities are low, a thermal conductivity will be close to a material-specific thermal conductivity. However, it is very difficult to measure a thermal conductivity at very low temperature. On the other hand, a thermal conductivity and an electrical conductivity at cryogenic temperature take very similar values. Moreover, electrical conductivity is relatively easy to measure even at extremely low cryogenic temperatures. Measuring the RRR ratio between a resistivity at room temperature and a resistivity at cryogenic temperature, it is possible to estimate a proportion of impurities.

The refrigerator has two stages of the cooling head. The first stage cooled to 40 K is for a thermal anchor. The cooling capacity is 40 W. Temperature of the 4.2K stage will reach to 3 K with no heat load. Cooling capacity at 4.2K stage is 1W. L-shaped copper plate stage of the sample cooling is fixed to the second 4.2K stage.

As a reference, at first, measurement of the RRR of Nb thin-film has been done. Nb thin-film on Si base plate, which was made by Kyoto University, was used. The sample were cooled at first to the superconducting state from room temperature, in order to confirm a resistance value to be a superconducting state. By utilizing the Joule heating caused by the measurement current, a resistance values with temperature increment were obtained at around transition temperature. Figure 5 shows measurement results with a measured current of 20 μA. Transition temperature at this time was 4.4 K, the resistance value was 2.54 x 10^{-6} [Ω]. Just above this transition temperature, the resistivity of the sample was 3.57 x 10^{-8} [Ω / cm], and resistivity around at room temperature extrapolated to 300K was 5.61 x 10^{-8} [Ω / cm]. Therefore, RRR of this sample could be determined to 1.57.

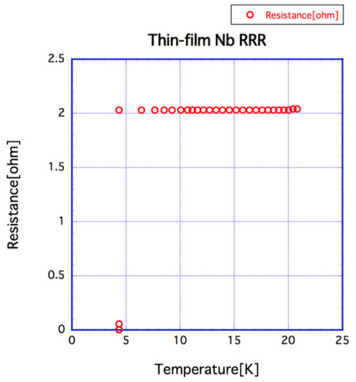

Figure 5: Resistance measurement of thin-film Nb sample with temperature increment.
(Current is 20μA. Tc = 4.4 K is observed.)

Transition temperature measurements were done, in case of NbN thin-film on Si baseplate fabricated by Saclay. In measurement for a current 20 μA, transition temperature at this time was 13.3 K, the resistance value was 1.50 x 10^{-1} [Ω]. Transition temperature of niobium nitride is measured to15.7 K in elsewhere, a film is seemed relatively good purity.

Transition temperature measurements is performed on Nb_3Sn foils supplied by FNAL. In measurement with 100μA, transition temperature at this time was 14.5 K, the resistance value was 4.30 x 10^{-4} [Ω]. Transition temperature of Nb_3Sn is measured to 18K in elsewhere, this Nb_3Sn sample is considered to be a relatively good purity, but there is some effect of Nb.

CONCLUSION

The design and fabrication of aluminum model cavity for the niobium cavity to measure an RF critical field of the multi-layer thin-film superconductor samples were carried out. The electrical design as well as the mechanical design were performed for the aluminum model cavity, then the cavity was fabricated and evaluated. To confirm the actual electromagnetic field distribution of the cavity with the calculated field, bead-pull measurement is under way. Different field distribution between measurement and calculation was observed. The study is on a way to resolve this issue.

In parallel, the RRR measurement system for purity evaluation and the transition temperature measurements of the thin-film superconductor was done. Nb thin-film, NbN thin-film and Nb_3Sn thin-film were measured to evaluate its purity.

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