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INSTRUMENTATION R&D FOR THE STUDIES OF SRF THIN-FILM STRUCTURES AT KEK AND KYOTO UNIVERSITY

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Abstract

We have been developing SRF instrumentations by which the effective lower critical magnetic field $H_{c1,eff}$ of superconducting-material sample is evaluated through the method of the third-order harmonic voltage measurement mainly for the studies of new SRF thin-film structures. Recently, the quad coil system, which enables us to measure four samples simultaneously in a single batch of an experiment, has been developed. In order to study the creation of thin-film structures inside the SRF cavity, we developed 3 GHz-shaped coupon cavities and an XT-map system for the performance tests of 3 GHz cavities. This article reports the details of these works.

INTRODUCTION

KEK and Kyoto University collaborate for the research to improve the performance of SRF cavities. Starting from a high-resolution camera system for defect detection in SRF cavities [1], various studies such as non-destructive inspection systems for SRF cavities [2], theoretical research on multilayer thin-film structures for high-Q/high-gradient SRF cavities [3-7], are conducted. One of the focused topics is the experimental investigation of thin-film superconducting structures, especially on superconductor-Insulator-Superconductor (S-I-S) structures, for performance enhancement of SRF cavities. In this article, we will report on the recent update result for studies of multilayer structure conducted by KEK and Kyoto University.

QUAD THIRD-ORDER HARMONIC DISTORTION MEASUREMENT SYSTEM

The measurement of effective lower critical magnetic field ($H_{c1,eff}$) for S-I-S thin-film structure is one of the important topics in the SRF community. Recently, it has been pointed out that the $H_{c1,eff}$ of a superconducting RF cavity might be increased by coating the inner surface of the cavity with a multilayer thin-film structure consisting of alternate insulating and superconducting layers [4, 5]. Generally, the $H_{c1,eff}$ of a superconducting material can be evaluated by applying an AC magnetic field to the material with a small coil and detecting the third-harmonic component in the coil voltage. This third-harmonic voltage component rises when the phase transition from the full Meissner state to the vortex-penetrating state happens. Hereafter, this method is called the third-harmonic voltage method. The measurement systems for third-harmonic voltage have been developed in CEA Saclay [8, 9], and later in Kyoto University [10] and KEK [11] in collaboration with CEA/Saclay. We have verified that the $H_{c1,eff}$ is enhanced for a sample with S-I-S structure that consists of NbN (200 nm) and SiO_2 (30 nm) formed on a pure Nb substrate that has an RRR of >250 [10, 11]. Recently, we have developed a new experimental setup for the third-harmonic voltage measurement system which allows us to measure four samples simultaneously in a single batch of the experiment. This feature can enhance the efficiency of the measurement cycle when the measurement is semi-automatic, as will be explained later. Figure 1 shows the 3D schematic view of the new experimental setup, consisting of four coil plates and a base plate made of aluminum. Four samples are mounted on the base plate (see Fig. 2). The coil plate is pressed down against each sample with a spring of appropriate pressure, and the distance between the coil plate and the sample is ensured by three ceramic balls embedded in the coil plate. Each coil plate has a cooling tab made of aluminum whose bottom area is immersed in liquid He (LHe). The temperature of the sample is controlled by a balance between the heater power and the heat flow through the cooling aluminum tab.

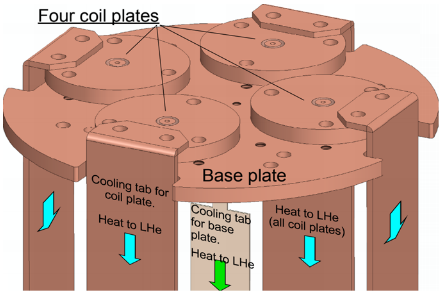

Figure 1: 3D schematic view of the third-harmonic voltage measurement system to measure four samples in a single batch of experiment.

Figure 2: Four coil plates on a base plate.

The coil is designed to achieve less power consumption while a strong magnetic field sufficient for the experiment (see Fig. 3). Since the center top area has less contribution to generate the magnetic field at the bottom side, the coil material at the conical area is removed. The concave coil is held by a ø7 sapphire ring and the magnetic field flux returns through the ring. The heat generated at the coil escapes through the sapphire ring to the aluminum plate, and then to the LHe through the aluminum tab. The coil wire is ø0.1mm and wound ~260 turns. The exciting current frequency f is 5 kHz. The excitation is pulsed and the macro pulse width τ is 100ms. The repetition rate is 1 Hz and the duty cycle is less than 10%. All of these parameters are typical and adjustable. The pulse operation is programmable and the sequence control of the parameters is possible (semi-automatic).

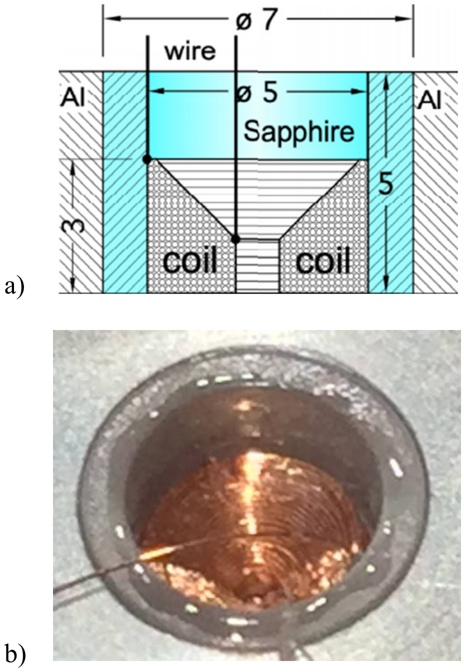

Figure 3: The small coil. a) Schematic illustration of the structure of the center of the coil plate. b) The concave coil fixed in the sapphire ring.

3 GHz SINGLE-CELL CAVITIES FOR STUDIES OF THIN-FILM STRUCTURE

Following the parameter search of thin-film structures by sample experiments, such as the third-order harmonic distortion measurements, performance tests with SRF cavity with various thin-film structures will be the important milestones to achieve enhanced cavity characteristics. Series of 3-GHz single-cell cavities are prepared for the studies of thin-film structures inside the cavity. We fabricated 3.0-GHz single-cell cavities with Cu and Nb materials for testing thin-film creations on the inner surface of the cavities in collaboration between Jefferson Laboratory (JLab) and KEK. The cavity was designed at JLab. According to the design of the cavity, the press-forming dies and trimming fixtures for the cavity-cell were also designed and fabricated at JLab. These dies and trimming fixtures were transported to KEK, and the rest of the fabrication processes were done at KEK. Nine 3.0-GHz single-cell Cu cavities with stainless-steel flanges and six 3.0-GHz single-cell Nb cavities with NbTi flanges were fabricated by the summer of 2019 [12]. Two 3.0-GHz single-cell Cu cavities were mechanically polished at JLab. Three 3.0-GHz single-cell Nb cavities were transported to JLab for inner-surface preparation by Electro-Polishing (EP) process. One 3.0-GHz single-cell Cu cavity and one 3.0-GHz single-cell Nb cavity were transported to CEA/Saclay for the collaborative studies of thin-film creation inside cavities. The rest of the cavities are used for the fitting tests in the construction of setup for performance tests of the 3-GHz single-cell cavities at KEK. All these Cu and Nb cavities are utilized for the tests of various thin-film creations at JLab, CEA/Saclay, and KEK.

The update of the fabrication status of 3-GHz single-cell cavities after 2019 is the machining of coupon cavities and the fabrication of two more 3-GHz single-cell Nb cavities with flanges made of low-RRR Nb.

Fabrication of 3-GHz Coupon Cavities

In the film-creation process of the cavity, it is important to keep the uniformity of film all over the inner surface of the cavity. To investigate the film quality at several positions of the cavity, like beam-pipe, equator, and cell-wall, we designed the 3.0-GHz single-cell cavity with detachable coupons. The 3D schematic view of the coupon cavity is shown in Fig. 4. A coupon Cu cavity and a coupon Nb cavity were made at Kyoto University by machining holes in the cavities which were already fabricated by 2019. In addition, one more coupon Cu cavity was made at KEK by machining holes in the cavity which was already fabricated by 2019. A picture of a coupon Cu cavity and a coupon Nb cavity is shown in Fig. 5.

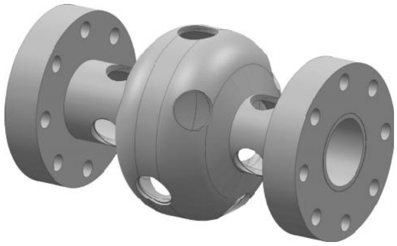

Figure 4: The 3D schematic view of the 3.0-GHz single-cell coupon cavity.

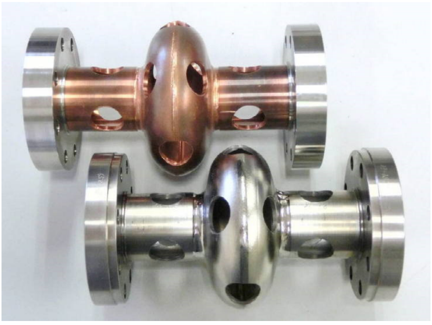

Figure 5: A picture of a coupon Cu cavity and a coupon Nb cavity.

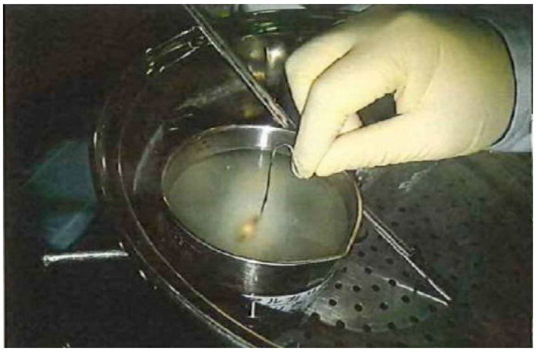

Figure 6: Surface-treatment process of a coupon Cu disk.

Figure 7: Coupon Cu disks packed in plastic bags after surface-treatment.

Coupon Cu disks were made at Kyoto University and the surface-treatments of coupon Cu disks were done at a company. A picture of the surface-treatment process of a coupon Cu disk is shown in Fig. 6 and a picture of coupon Cu disks packed in plastic bags.is shown in Fig. 7. These coupon Cu disks were set into a coupon Cu cavity and a test of Nb thin-film creation was done at ULVAC inc. The Nb thin-films created on the coupon Cu disks are under analysis in various methods. A picture of a coupon Cu cavity with coupon-fixture is shown in Fig. 8.

Figure 8: A picture of a coupon Cu cavity with coupon-fixture.

Fabrication of 3-GHz Single-Cell Nb Cavities with Flanges of Low-RRR Nb

Ti material in the NbTi flange of the Nb cavity might affect the thin-film creation of Nb_3Sn on the inner-surface of the cavity. In order to eliminate this possibility, we fabricated two 3-GHz single-cell Nb cavities with flanges of low-RRR Nb. The seal on the flanges of low-RRR Nb will be done by Indium wires because of the softness of low-RRR Nb material. A picture of a 3-GHz single-cell Nb cavity with flanges of low-RRR Nb is shown in Fig. 9. We are planning to fabricate several more 3-GHz single-cell Nb cavities with flanges of low-RRR Nb.

Figure 9: A picture of 3-GHz single-cell Nb cavity with flanges of low-RRR Nb.

XT-map System for 3 GHz Cavities

An X-ray and temperature mapping system (XT-map) is under development for the vertical test of the 3-GHz single-cell cavities. In this system, the same technology as the XT-map, developed in Kyoto University [1], for 1.3-GHz cavities is used. Figure 10 shows the design geometry of the XT-map system for a 3-GHz single-cell cavity.

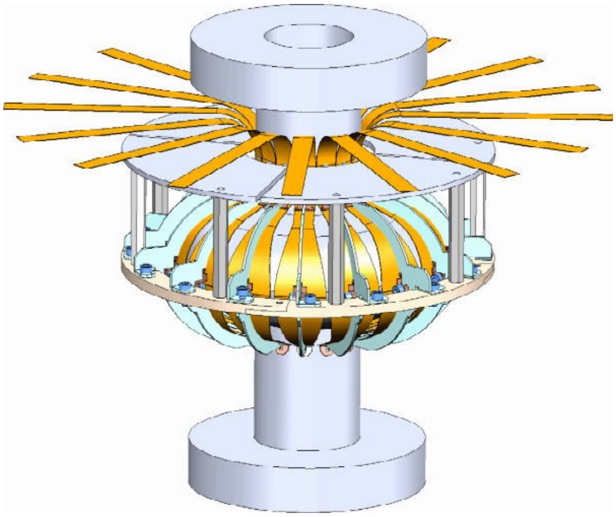

Figure 10: Image of assembled XT-map.

Figure 11: A picture of flexible printed circuits and Aluminum jigs.

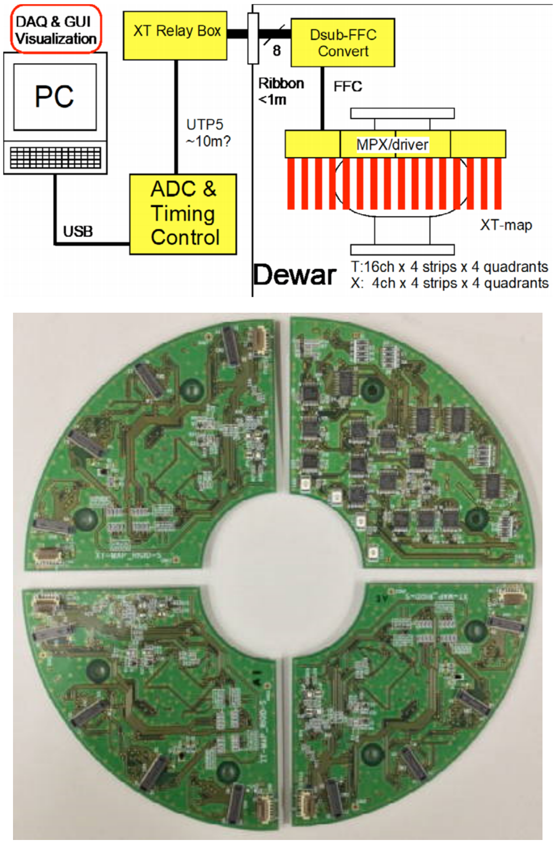

Figure 12: Schematic of signal-flow of XT-map system (upper) and control boards for XT-map (lower). The board on the top right shows the side of the installed component. The other three boards show four connectors for the sensor leaf and connectors for interconnection at both ends.

As detection elements, RuO (Ruthenium Oxide) chip resistors for cryogenic temperature measurement and infrared photo-diodes for X-ray detection are mounted on 16 flexible printed circuit leaves (Fig. 11). The temperature sensors on these flexible printed circuit sheets are pressed against the cavity surface by a phosphor bronze leaf spring supported by an aluminum jig. The signals from the sensors (change in RuO resistance and charge stored in the photodiode) are converted to voltage signals and scanned by the multiplexer on the control board (Fig. 12). The typical scanning rate is 10 Hz. All the active devices on the control boards are CMOS devices that can work even in cryogenic temperatures. By scanning of sensors in the cryostat for the vertical tests, the number of cables for readout can be significantly reduced compared with the number of sensors. This reduces the time and cost of preparation work for each vertical test. Less number of wires also reduces the heat intrusion to the cryogenic area and equipment cost. These contribute to the cost reduction for mass production of cavities. Figure 13 shows the 3D drawing view of the top flange and supporting structure of the 3-GHz single-cell cavity with XT-map system in the cryostat of the vertical performance test.

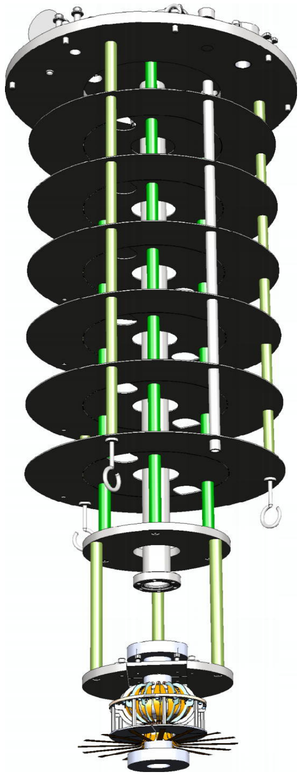

Figure 13: 3D drawing view of top flange and supporting structure of 3-GHz single-cell cavity with XT-map system in the cryostat of vertical performance test.

CONCLUDING REMARKS/ FUTURE PLAN

If we consider the series of experimental results from third-harmonic measurements of samples with various artificial thin-film structures and also the theoretical understanding of the phenomena, now we are confident that some artificial thin-film structures on the inside surface of the SRF cavity might enhance the performance of accelerating gradient. Although it is difficult to study the improvement of Q-value with sample experiments, the improvement of Q-value might be also possible from recent theoretical considerations. The next step forward us is the experiments with cavities. We should create various artificial thin-film structures on the inside-surface of cavities and conduct the performance tests to prove the practical application of this technology to the particle accelerators. However, the resources for the thin-film studies are still very much limited in physics/accelerator groups of laboratories and universities in the world. In such a situation, it is important to extend the collaborative network more in the world to be widely coherent.

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REFERENCES

[1] Y.Iwashita, H.Hayano, and Y.Tajima, "Development of high resolution camera and observations of superconducting cavities", *Phys. Rev. ST Accel. Beams*, vol. 11, p. 093501, 2008. `doi:10.1103/PhysRevSTAB.11.093501`

[2] Y. Iwashita, H. Hayano, Y. Kuriyama, and H. Tongu, "Updates on the Inspection System for SRF Cavities", in *Proc. 19th Int. Conf. RF Superconductivity (SRF'19)*, Dresden, Germany, Jun.-Jul. 2019, pp. 1111-1113. `doi:10.18429/JACoW-SRF2019-THP088`

[3] T Kubo, Y Iwashita, and T Saeki, "Radio-frequency electromagnetic field and vortex penetration in multilayered superconductors", *Appl. Phys. Lett.*, vol. 104, p. 032603, 2014. `doi:10.1063/1.4862892`

[4] T. Kubo, "Multilayer coating for higher accelerating fields in superconducting radio-frequency cavities: a review of theoretical aspects", *Supercond. Sci. Technol.*, vol. 30, p. 023001, 2017. `doi:10.1088/1361-6668/30/2/023001`

[5] T. Kubo, and A Gurevich, "Field-dependent nonlinear surface resistance and its optimization by surface nanostructuring in superconductors", *Phys. Rev. B*, vol. 100, p. 064522, 2019. `doi:10.1103/PhysRevB.100.064522`

[6] T. Kubo, "Superfluid flow in disordered superconductors with Dynes pair-breaking scattering: Depairing current, kinetic inductance, and superheating field", *Phys. Rev. Res.*, vol. 2, p. 033203, 2020. `doi:10.1103/PhysRevResearch.2.033203`

[7] T. Kubo, "Superheating fields of semi-infinite superconductors and layered superconductors in the diffusive limit: structural optimization based on the microscopic theory", *Supercond. Sci. Technol.*, vol. 34, no. 4, p. 045006, 2021. `doi:10.1088/1361-6668/abdedd`

[8] C. Z. Antoine *et al.*, "Optimization of tailored multilayer superconductors for RF application and protection against premature vortex penetration", *Supercond. Sci. Technol.*, vol. 32, no. 8, p, 085005, 2019. `doi:10.1088/1361-6668/ab1bf1`

[9] C. Z. Antoine *et al.*, "Progress on Characterization and Optimization of Multilayers", in *Proc. 18th Int. Conf. RF Superconductivity (SRF'17)*, Lanzhou, China, Jul. 2017, pp. 368-373. `doi:10.18429/JACoW-SRF2017-TUYBA01`

[10] R. Katayama *et al.*, "Evaluation of the Superconducting Characteristics of Multi-Layer Thin-Film Structures of NbN and SiO_2 on Pure Nb Substrate", in *Proc. 19th Int. Conf. RF Superconductivity (SRF'19)*, Dresden, Germany, Jun.-Jul. 2019, pp. 807-809. `doi:10.18429/JACoW-SRF2019-THFUA2`

[11] H. Ito *et al.*, "Lower Critical Field Measurement of NbN Multilayer Thin Film Superconductor at KEK", in *Proc. 19th Int. Conf. RF Superconductivity (SRF'19)*, Dresden, Germany, Jun.-Jul. 2019, pp. 632-636. `doi:10.18429/JACoW-SRF2019-TUP078`

[12] T. Saeki *et al.*, "Fabrication of 3.0-GHz Single-cell Cavities for Thin-film Study", in *Proc. 19th Int. Conf. RF Superconductivity (SRF'19)*, Dresden, Germany, Jun.-Jul. 2019, pp. 177-181. `doi:10.18429/JACoW-SRF2019-MOP054`