

Study on the Superconducting Performance of Ultra-fine Strand Nb₃Al Cables

Ryuichi Ueki , Norihito Ohuchi , Akihiro Kikuchi , Masaru Yamamoto, Kazuyuki Aoki, and Yasushi Arimoto 

Abstract—In the straight beam lines of the SuperKEKB Tsukuba area, 16 conventional sextupole magnets have been installed at intervals of 20–35 m. To achieve high luminosity, higher precision beam tuning with sextupole magnets is required. In KEK, a study on a superconducting sextupole magnet system involving three types of corrector magnets is ongoing. Considering the operating temperature of the system, an A15 compound superconductor, Nb₃Al, is being studied for use as the cable material, and the development of the reaction and winding coil production with Nb₃Al cable has been attempted. This study developed an Nb₃Al ultra-fine strand superconducting cable with a strand of $\phi 50 \mu\text{m}$ for the corrector magnets, and the critical currents of the cable were measured as functions of the bending radius and the temperature. This paper reports the temperature dependence of the critical currents of the bent Nb₃Al cables after heat treatment.

Index Terms—Critical current, Nb₃Al cable, super fine strand, superconducting sextupole magnet, superconducting corrector magnet, superkekb.

I. INTRODUCTION

SUPERKEKB is an asymmetric electron-positron circular collider with a luminosity of 4.65×10^{34} (realized in June 2022), which is twice that of the KEKB luminosity [1], [2]. To achieve even higher luminosity, a precise correction of chromatic coupling is required. In particular, the magnetic field quality of sextupole magnets located in the local chromaticity correction [3] area on both sides of the collision point exerts a significant impact on the beam colliding performance and requires a more precise magnetic field adjustment. Therefore, we are considering replacing these sextupole magnets with superconducting sextupole magnets and using corrector coils to precisely control the sextupole magnetic field [4], [5]. The magnetic field design of the superconducting magnet is adjustable according to the arrangement of the superconductor wire that formed the superconducting coil. Correction of the field rotation and

shift of the field center could be performed by superconducting correction magnets built into the bore of the sextupole magnet. Because of a limited space inside the sextupole magnet, the coil design is based on the thin multilayer coil system used in the final focus of the superconducting quadrupole magnets of SuperKEKB [6]. Furthermore, because the magnet cryostat is cooled by a cryocooler, we plan to produce corrector magnets using a superconductor with a higher critical temperature than NbTi wires. A. Kikuchi et al. developed the technique of drawing the Nb₃Al wire to $\phi 30 \mu\text{m}$ [7], [8]. The thin strands reduce the strain on the cable during winding, which is expected to mitigate the degradation of superconducting properties. We have investigated the properties of the cable one of the candidates, that is, Nb₃Al ultrafine strand wire cables for application in corrector magnets fabricated by the reaction and winding method. The wire was made of Nb and Al sheets with the jelly-roll method. The annealing condition of the wire is 800 °C for 10 hours. In a previous study, we evaluated the fundamental properties of a short straight cable that comprised a 49-strand Nb₃Al cable with $\phi 50 \mu\text{m}$ strands, which had a critical current of 86 A at 4 T and 6 K, which exceeded the corrector magnet specification of 50 A [9]. Because a critical current of the A15 superconducting conductor degrades owing to the bending strain [10], it is important to investigate its dependence on the bending strain. In this paper, we report the results of a mechanical bending test of a Nb₃Al cable, measurements of the critical current of the bent cables in relation to the radii of curvature, and the critical current of cable in a shape of solenoid coil.

II. BENDING TEST OF Nb₃AL CABLE

A mechanical bending test was conducted on a $\phi 50 \mu\text{m}$, 49-strand Nb₃Al cable. The cable consisted of 49 evenly twisted strands (Fig. 1). The cables were wrapped around cylindrical copper blocks with diameters of 50, 45, 40, 35, 30, 25, 20, and 15 mm. The results are shown in Fig. 1. The cable was not visibly damaged when the radius of curvature was between 25 and 15 mm. The cable snapped completely with a 12.5 mm radius of curvature. The two samples yielded similar results (red arrows in Fig. 1). In the 49-strand cable, the strands were densely packed and subjected to bending stress with the strands fixed to each other, which is considered to have caused the breakage. In the design of coils for accelerators, such as SuperKEKB, a smaller bending radius is advantageous. Therefore, we developed a cable that could be bent to a smaller radius of curvature. We fabricated a twisted wire using 7 strands and then fabricated a 7×7 strand

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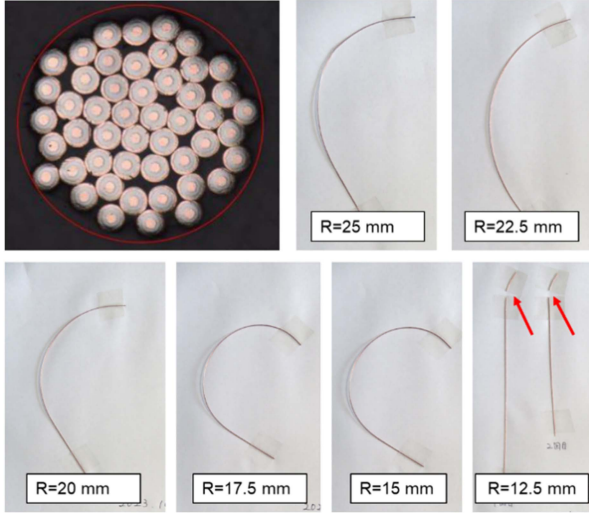


Fig. 1. Photograph of the cross section of the 49-strand twisted Nb_3Al cable and the results of the bending test.

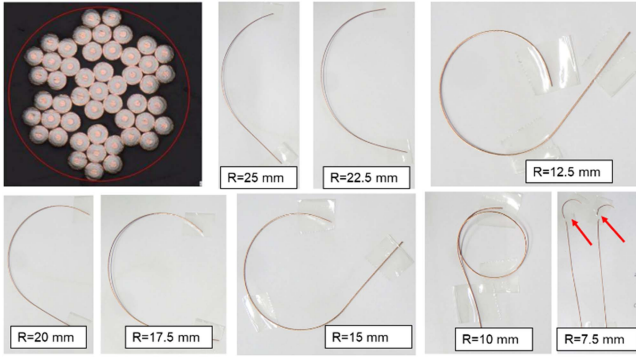


Fig. 2. Photograph of the cross section of the 7×7 strand twisted Nb_3Al cable and the results of the bending test.

Nb_3Al cable using the seven twisted wires. The cross-section of the 7×7 strand cable is shown in Fig. 2. The space between the strands was wider than that of the 49-strand cable. The 7×7 strand cable exhibited no visible damage when the radius of curvature was 10 mm or larger, and the cable broke when the radius of curvature was 7.5 mm (red arrows in Fig. 2). Thus, the 7×7 strand cable has the potential to produce coils with a smaller bending radius.

III. CRITICAL CURRENT MEASUREMENT

A. Critical Current Measurement of Short Straight Cable

We measured the critical current in a 7×7 strand Nb_3Al cable. The critical current of a short straight cable 80 mm in length under 0 T was measured to investigate its basic characteristics. The folder used for the measurements is shown in Fig. 3. The cable was embedded and soldered in a $0.6 \text{ mm} \times 0.6 \text{ mm}$ groove machined into a $2 \text{ mm} \times 1 \text{ mm}$ copper plate. A signal wire for measuring the sample voltage was attached to both ends of the sample, and the transition of the cable to the normal state was observed. A 40Ω sheet heater was installed on the opposite side of the copper plate to the cable to control the temperature of

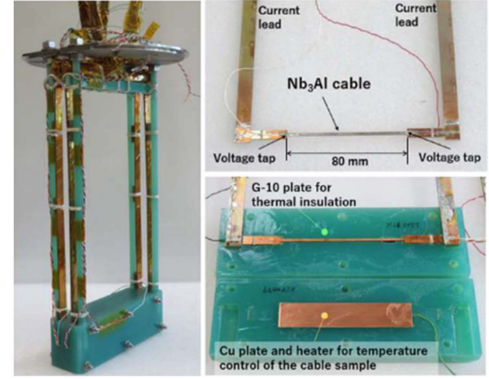


Fig. 3. Folder of straight current test.

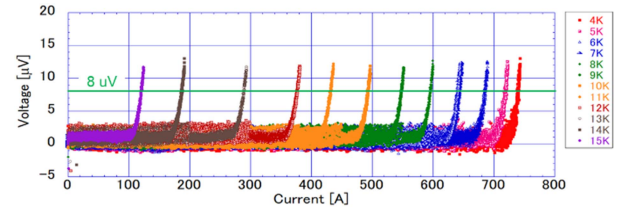


Fig. 4. Variation in the voltage on both sides of the sample with respect to the applied current at various temperatures.

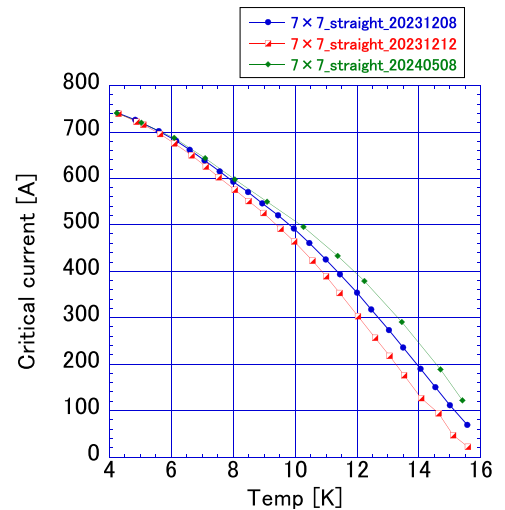


Fig. 5. Critical current as a function of sample temperature in the linear current test.

the cable. The cable temperature was measured using a Cernox thermometer [10] or a carbon resistance thermometer calibrated using a Cernox thermometer. The critical current was measured as the cable temperature increased by 1 K using the heater.

Fig. 4 shows the voltages at both ends of the sample with respect to the applied current at each temperature. The critical current was evaluated as the current at which the voltage reached $8 \mu\text{V}$ based on a criterion of $1 \mu\text{V}/\text{cm}$ [12].

The temperature dependence of the critical current is shown in Fig. 5. The critical current at 4.2 K was 740 A, which is higher than that of the 49-strand Nb_3Al cable. The results of the three measurements showed that the critical current at each temperature was approximately the same from 4.2 K to 6 K,

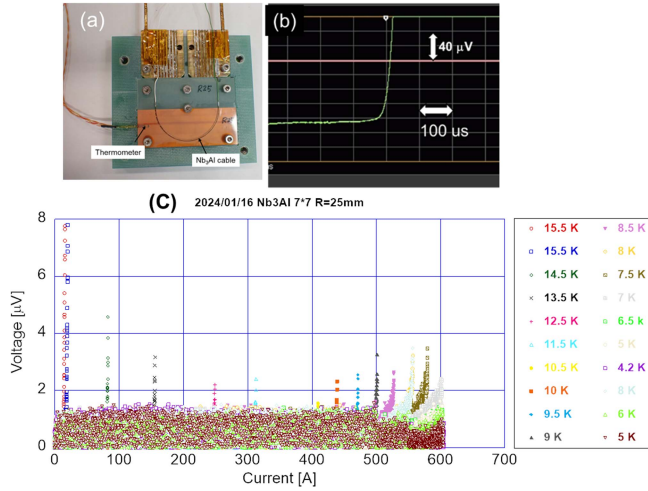


Fig. 6. (a) Measurement folder of the bending current test. (b) Voltage waveform at the normal transition of the cable. (c) Voltage of the bent cable in relation to the temperature of the bent cable.

but variations were observed in the higher temperature range than 6 K. The spaces in the measurement folder were filled with APIEZON grease. Slight differences in the thermometer mounting could have changed the thermal conductivity, resulting in variations in the temperature measurements. The variation was ± 0.8 K for the same critical current value at approximately 14 K. Establishing an accurate temperature measurement method is difficult to control when measuring critical current over the temperature of 6 K. Because the variation in the temperature measurement was small in the region of 6 K, it was assumed that there was no problem in evaluating the critical current in the coil specification.

B. Critical Current Measurement of Bending Cable

The effect of the mechanical bending strain on the critical current was investigated. Fig. 6(a) shows the critical current measurement folder of a 7×7 strand Nb₃Al cable with a radius of curvature of 25 mm. A groove with a radius of 25 mm was created using a G10 plate. A Nb₃Al cable was set in the groove. A copper wire was attached to the cable to shunt the current and prevent it from melting when the Nb₃Al cable transitioned to the normal state. The voltage at both ends of the bent sample was measured. The sample temperature was controlled using a 60 Ω sheet heater on the copper plate and measured with a Crenox thermometer or a carbon resistance thermometer that was calibrated using a Cernox thermometer. The measurement was taken under 0 T.

Fig. 6(c) shows the voltages at both ends of the Nb₃Al cable with respect to the applied current. In contrast to the short straight-sample test, the power supply was shut off by a quench detector when the voltage reached sub microvolt levels. Measurements using a high-speed multi-recorder (GR-7500: KEYENCE) exhibited an instantaneous voltage increase (Fig. 6(b)). A voltage rise owing to normal transition of the cable was observed. Because the voltage did not reach the 1 μ V/cm criteria, the current at which the transition occurred was used

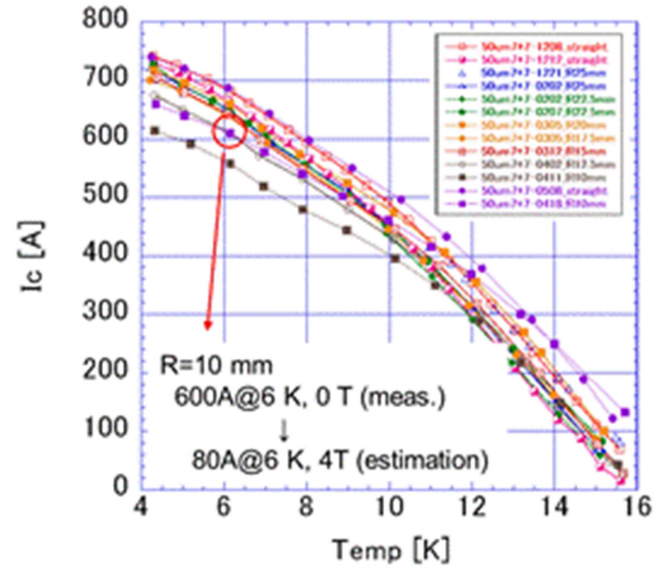


Fig. 7. Critical current as a function of sample temperature in the bending current test.

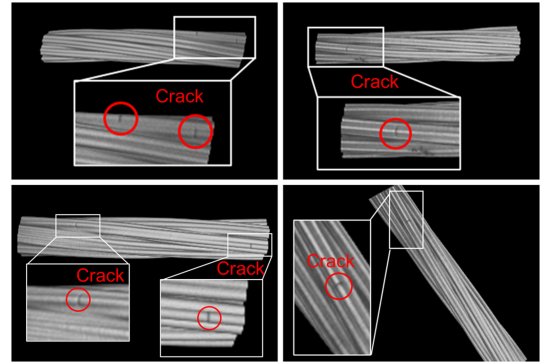


Fig. 8. CT image of the Nb₃Al cable with the highest degradation of critical current ($R = 10$ mm).

as the critical current. Fig. 7 shows the critical currents at each bend radius. The critical currents for cable curvature radii of up to 15 mm were approximately the same. The critical currents for cables with radii of curvature of 12.5 mm and 10 mm were clearly lower at temperatures below 8 K. The CT image of Nb₃Al cable with the highest degradation (sample ID: 50 μ m 7×7 -0411_R10 mm) is shown in Fig. 8. Certain cracks were observed. These cracks decreased the critical current.

We estimated the critical current of a 7×7 strand Nb₃Al cable when an external magnetic field was applied. Because the same strands were used in both the 49 and 7×7 strand cables, the degree of degradation in response to an external magnetic field was expected to be the same. We calculated the critical current of a 7×7 strand cable based on the previously measured external magnetic field dependence characteristics of a 49-strand Nb₃Al cable. The critical current of the 49-strand Nb₃Al cable under 4 T was about 14% of the critical current under 0 T [8]. The critical current of the 7×7 strand Nb₃Al cable at 6 K and 0 T was greater than 600 A. Using this value, the critical current at 6 K and 4 T was estimated to be approximately 80 A, which is

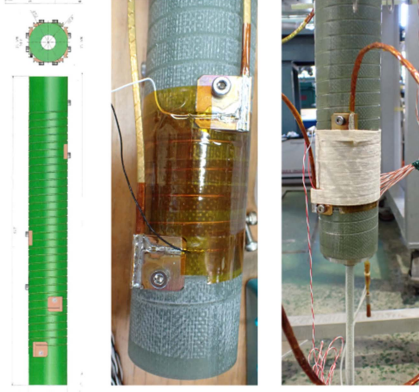


Fig. 9. Measurement folder of solenoid coil.

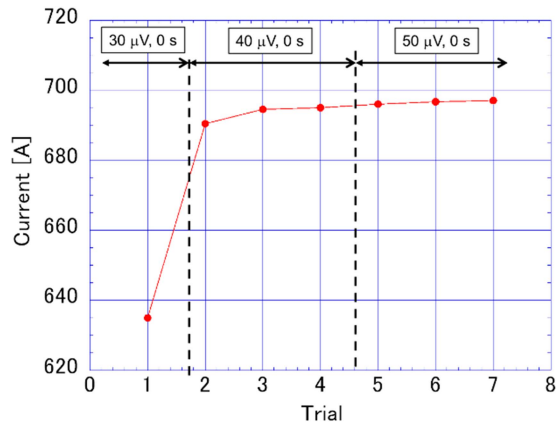


Fig. 10. Change in maximum current value with quench detector setting.

sufficiently high compared to the specification value of 50 A. In the future, we plan to measure the critical current under an external magnetic field.

IV. CRITICAL CURRENT MEASUREMENT OF THE SOLENOID SHAPE CABLE

A solenoid coil with 5 turns was fabricated, and the critical current of the cable was measured. The effect of continuous bending strain on the critical current of the cable was measured. Fig. 9 shows the measurement procedure. The groove was made on a spiral in a cylindrical G10 with a diameter of 50 mm, and an Nb_3Al cable was wrapped around the groove. The groove was filled with a glue to fix the Nb_3Al cable such that it would not move owing to the Lorentz force. The folder was then immersed in liquid helium, and the critical current at 4.2 K was measured.

Fig. 10 shows the maximum current for the same sample for seven applied current test cases. In the first trial, the quench detector was activated upon the application of a current of approximately 635 A. This current was lower than the value of 730 A obtained in the bending test ($R = 25$ mm) described in the previous section. The voltages at both ends of the sample during the test were measured using an oscilloscope, and the voltage waveform shown in Fig. 11 was frequently observed when the applied current exceeded 600 A. The voltage surged for a few

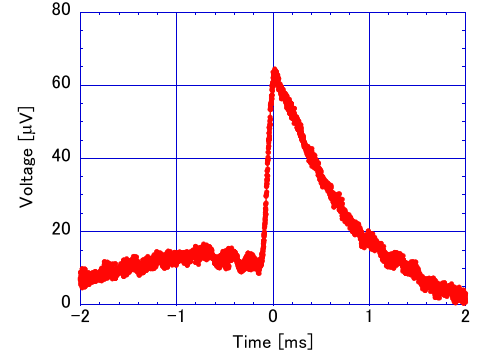


Fig. 11. Voltage waveform by cable motion.

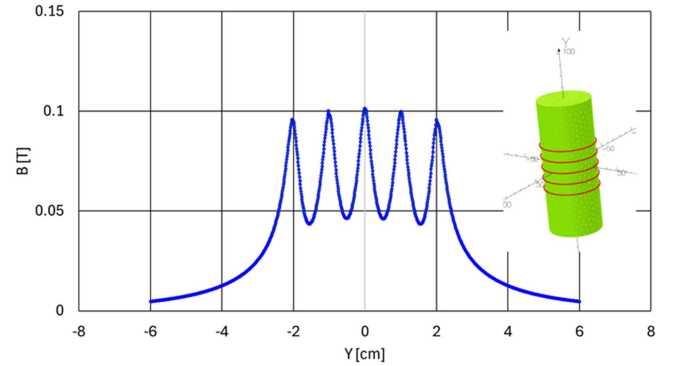


Fig. 12. Simulation of magnet field by 3D-OPERA.

milliseconds and then quickly decayed. This was attributed to the movement of the cable or strands owing to the Lorentz force produced by the solenoid. The conditions for the quench detector in the first trial were $30 \mu\text{V}$ for 0 s. We changed the setting such that the quench detector would not work because of the cable movement.

Finally, the power supply was shut off via cable quenching under a quench detector condition of $50 \mu\text{V}$ for 0 s, and the maximum current was increased to 697 A. This value was also lower than 730 A. We made a simple model and calculated the magnetic field near the coil using OPERA-3D (Fig. 12). The magnetic field generated by the solenoid coil itself was approximately 0.1 T. We think that this magnetic field caused the critical current to decrease by 680 A.

V. SUMMARY

We evaluated the superconducting properties of a $\phi 50 \mu\text{m}$ Nb_3Al ultrafine strand superconducting cable. The 7×7 strand cable could be bent to a radius of curvature of 10 mm and exhibited a critical current of over 600 A at 6 K and 0 T. It was found that a cable in shape of 50 mm-diameter solenoid could transport the current of 697 A, which is almost same as the critical current of the straight sample. We will measure the critical currents of the bending cable and solenoid coil in an external magnetic field and performed tests on smaller-diameter solenoid coils.

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