Development of Super Fine Strand Nb_3Al Cable for SuperKEKB Superconducting Sextupole Magnet System

N. Ohuchi, A. Kikuchi, M. Yamamoto, X. Wang, K. Tsuchiya, K. Aoki, Y. Arimoto, T. Oki and Z. Zong

***Abstract*— Along the beam lines of the SuperKEKB main rings, 218 conventional sextupole magnets are installed, and they are used for tuning the chromaticity of the accelerator rings. Especially, 16 sextupole magnets in the beam straight lines in the Tsukuba area are quite essential for the Crab Waist beam colliding. To make the beam tuning process finer, we are studying the superconducting sextupole magnet system with three types of the corrector magnets. From the operation temperature of the system, A15 compound superconductor is chosen as the cable material, and the development of the react and wind coil production has been tried with the Nb_3Al cable. The Nb_3Al super fine strand superconducting cable for the corrector magnets was manufactured, and its superconducting characteristics are being studied. In this paper, as the first test result of the development, the critical current characteristics of the straight cable as variables of temperature and magnetic field are reported. As the results, the critical current of the Nb_3Al cable was higher than the design values for the corrector magnets, and this level of cable performance also indicates the potential for the cable being used for the main sextupole magnet.**

***Index Terms*—Nb_3Al cable, super fine strand, critical current, superconducting sextupole magnet, superconducting corrector magnet, SuperKEKB**

I. Introduction

SuperKEKB is the electron-positron collider [1] which succeeded in the first collision of 7 GeV electron and 4 GeV positron on April 26, 2018, and the colliding luminosity reached 4.650×10^{34} $cm^{-2}s^{-1}$ in the beam operation on June 8, 2022. In tuning the beam colliding condition, the normal sextupole magnets along the accelerator rings have an important function in the local chromaticity correction. Especially, the 16 sextupole magnets along the beam straight section in the Tsukuba area of the main ring are being operated for the Crab Waist beam collision [2].

The study for upgrading the 16 normal sextupole magnets to the superconducting magnet with the correctors is going on. From the space constraint of the magnet-cryostat in the accelerator beam lines, the magnets in the cryostat are nested in the cryostat. The 16 magnets are set at intervals of 20 m ~ 35 m along the beam lines of 220 m long. The magnet-cryostats are expected to be separately cooled with a cryocooler. With the studies of this magnet system, the superconducting cable which has a higher critical temperature than NbTi was investigated. As the cable material, we have chosen Nb_3Al, and the diameter of the strand in the cable was reduced to 50 μm for applying the react-and-wind method to the coil fabrication. In this paper, the temperature and magnetic field dependences on the critical current of the Nb_3Al cable are reported.

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II. Sextupole and Corrector Magnets

A. Normal sextupole magnets in the beam lines

The magnetic parameters of the normal sextupole magnets along the beam straight lines in the Tsukuba area are shown in Table I. The design field gradient is 480 T/m^2. The yoke lengths of the magnets are different due to the required integral magnetic field for each beam energy. On each beam line, 4 sextupole magnets are placed on both sides across the beam colliding point. The turn number of the coil is 22, and the conductor current is 600 A. The sextupole magnets for the LER have the mechanical revolution function to adjust the midplane angle of the sextupole field.

TABLE I
Design Parameters of The Normal Sextupole Magnets in The SuperKEKB Tsukuba Beam Lines

	LER	HER	
Magnetic field strength (T/m^2)	480	480	
L_{yoke} (m)	0.3	0.6	0.5
Current (A) × turns/pole	600 ×22	600 ×22	
Number of magnets	8	4	4

where, LER is the Low Energy Ring of positron at 4 GeV, and HER is the High Energy Ring of electron at 7 GeV. L_{yoke}, means the length of the iron yoke.

B. Targeted superconducting sextupole magnet system with corrector magnets

SuperKEKB is operated in the flat-top beam current mode, and then the magnets are operated with a constant current during beam operation. The conceptual magnetic parameters of the superconducting sextupole magnet and the correctors are shown in Table II. The superconducting sextupole magnet is designed to generate the field gradient higher than 800 T/m^2.

The effective magnetic length is shorter than 0.3 m because the present space constraints of the normal sextupole magnets on the beam lines are required to be preserved. The magnet current is designed to be smaller than 250 A because of the available cooling power of the cryocooler.

The corrector magnets in the system are the skew sextupole magnet (A_3), the normal and skew quadrupole magnets (B_2, A_2). The coils of magnets are multi-layered, and they are placed in the sextupole magnet bore. Because the corrector magnets are designed to be impregnated with epoxy between the coil layers and the correctors, the ramping ratio of the current is less than 5 A/s not to have the temperature rise by the AC loss.

TABLE II
CONCEPTUAL MAGNETIC PARAMETERS OF THE SUPERCONDUCTING SEXTUPOLE MAGNETS AND CORRECTORS

Sextupole magnet	
Sextupole field gradient (T/m²)	> 800
Effective magnetic length (m)	< 0.3
Current (A)	< 250
Superconductor material	Nb_3Al
Superconducting correctors	A_3, B_2, A_2
Superconductor material	Nb_3Al
A_3 corrector magnet	
Sextupole field gradient (T/m²)	> 125
Current (A)	< 50
B_2, A_2 corrector magnets	
Quadrupole field gradient (T/m)	> 0.4
Current (A)	< 50

III. DEVELOPMENT OF SUPER FINE STRANDS Nb_3Al CABLE

The magnets in the system are nested, and the corrector magnets are multi-layered. Therefore, we are looking for the react and wind method in the process of the coil production with the A15 conductor. The A15 conductor has a strong strain dependence of the critical current (I_c), and this superconducting characteristic becomes a tough problem to be solved in the coil production. The strain sensitivities on the critical current of the Nb_3Sn and Nb_3Al cables were compared [3], and the Nb_3Al cable showed the smaller strain sensitivity than the Nb_3Sn cable. And the thin strand in the superconducting cable leads to the reduction of the cable strain during winding the coil. A. Kikuchi *et al.* developed the technique of drawing the Nb_3Al wire to ϕ 30 μm [4], [5], and eventually this technology was introduced to the development of the superconducting sextupole magnet system for SuperKEKB.

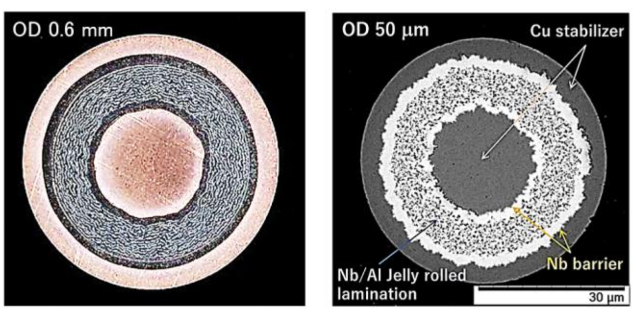

Fig. 1. Cross sections of the Nb_3Al wire. The left is the ϕ0.6 mm wire during drawing process, and the right is the ϕ50 μm wire.

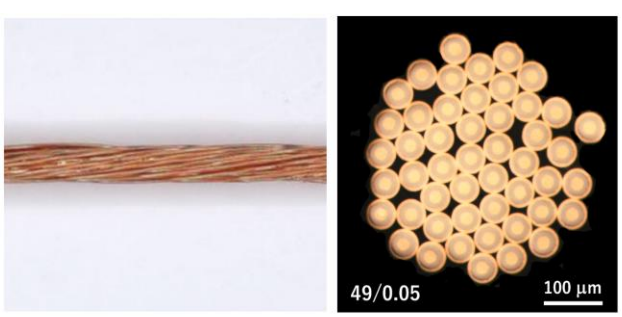

Fig. 2 49 Nb_3Al strand cable external view and the cross section.

In Fig. 1, the cross sections of the Nb_3Al strand wire of ϕ 0.6 mm and ϕ 50 μm are shown. The wire was made of Nb and Al sheets with the jelly-roll method. In Fig. 2, the external view, and the cross section of the 49 Nb_3Al strand cable are shown. The strand diameter is ϕ 50 μm, and the cable consists of 49 strands, which are twisted evenly. The equivalent diameter of the cable is ϕ 0.42 mm, and that is the circumscribing circle of the cable where all strands are set closely in a circle. The parameters of the cable are listed in Table III.

TABLE III
PARAMETERS OF Nb_3Al CABLE FOR CORRECTOR MAGNETS

Nb_3Al cable	
Number of strands	49
Equivalent diameter (mm)	0.42
Cabling pitch [S] (mm)	8.0
Heat treatment temp. and time (°C/H)	800 / 10
Requirement of the transport current @ 4 T and 6 K (A)	50
Strand wire	Jelly-rolled wire
Strand diameter (μm)	50
Cu ratio	1.0

IV. CRITICAL CURRENT MEASUREMENT OF Nb_3Al CABLE

A. *Sample holder and the test stand*

The Nb_3Al cable was heat-treated in linear shape. The temperature and the period were 800 °C and 10 hours. The test cable sample of 150 mm length was embedded in the groove of the Cu test plate and soldered to it as shown in Figs. 3 and 4. The cross section of the Cu plate for measuring the resistive voltage at normal transition was 2 mm×1 mm, and the groove size was 0.6 mm×0.6 mm. The length of this area was 80 mm long. The voltage taps were soldered to both ends of the area. The temperature was measured with the CERNOX sensor [6]. The sensor was attached to the Cu plate with an Apiezon grease [7] as shown in Fig. 4. The temperature control of the test area was performed with the film heater and the Cu plate of 0.5 mm thickness, 16 mm width and 80 mm length. The film heater was attached to the surface of the Cu plate with the grease, and the cable sample placed in the non-heater side of the Cu plate. By the configuration of the components, the cable temperature was uniformly controlled along the length. The test Cu plate was connected to the current leads with solder. The cable sample, the sensor, the heater, and the Cu plate were set between the two G-10 plates. In the clearance gaps between the components, the grease was filled. The assembled test holder is shown in Fig. 3. With the test holder, two cable samples can be tested at once. The whole holder is cooled with liquid helium, and the G-10 plates have a function of thermal insulation between the cable sample and liquid helium.

The test holder was placed in the bore of the superconducting solenoid which can generate magnetic field up to 5 T. The axis of the cable was perpendicular to the solenoid field. The solenoid length was 634 mm, and the inner diameter of the coil was 190 mm. The solenoid generated a uniform solenoid field to the cable sample.

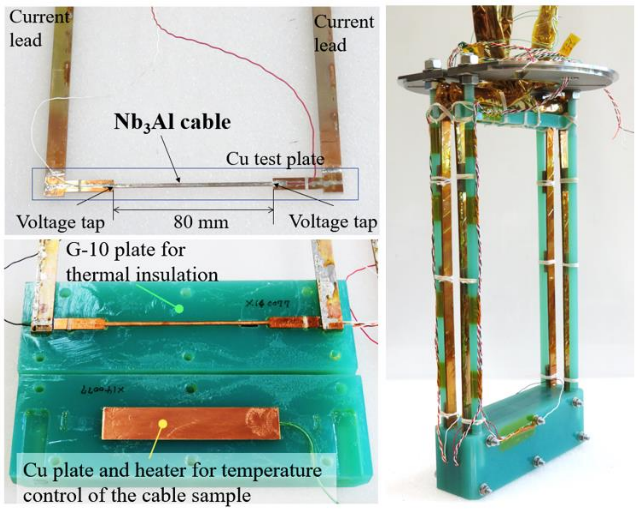

Fig. 3. Cable test holder. The top left picture shows the sample embedded in the Cu plate. The bottom left shows the test sample, the Cu plate for temperature control, and G-10 plates. The right one is the assembled test holder.

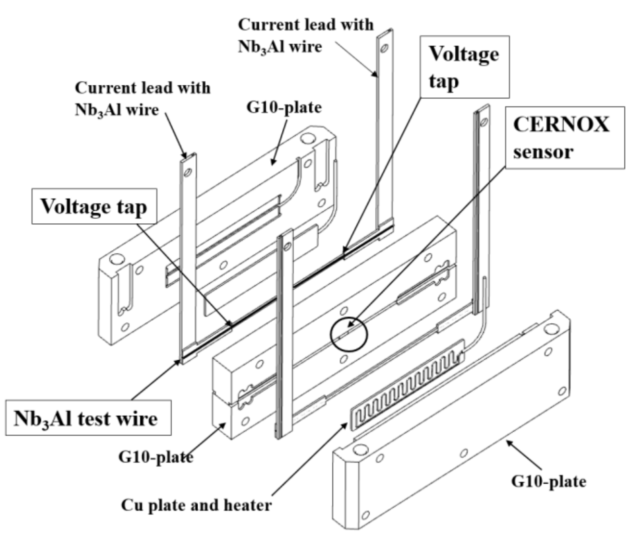

Fig. 4. Assembly of Nb_3Al cable sample test holder.

B. *Measurements of the Nb_3Al cable critical current*

The measurement of the critical current of the Nb_3Al cable was performed as follows:

1. The sample temperature was increased from the liquid helium temperature to the target temperature by the heater.
2. The sample temperature was measured by the CERNOX sensor. The required time for stabilizing the sample temperature was about 5 minutes.
3. The current to the Nb_3Al cable sample was increased in two steps. From 0 A to the current near to the critical value, the increase rate was 3 A/s, and afterward the rate was set at 1 A/s.

As an example of the measurements, the current, the voltage and the temperature of the sample at the solenoid field (B_s) = 0 T are shown in Fig. 5. In the plots, the x-axis is the time in second from the starting point of increasing the current. In the measurement, the cable temperature at x=0 was set at 5.91 K. The current was increased by 3 A/s to 550 A, and afterward 1 A/s to 638 A at which the power supply was cut off. At the current of 625 A, the voltage was induced by the normal transition in the cable, and the temperature started to rise by Joule heating. The *n* value was 192. The *n* value is smaller than the value of only the cable because the cable was soldered to the Cu plate, as shown in Fig. 3.

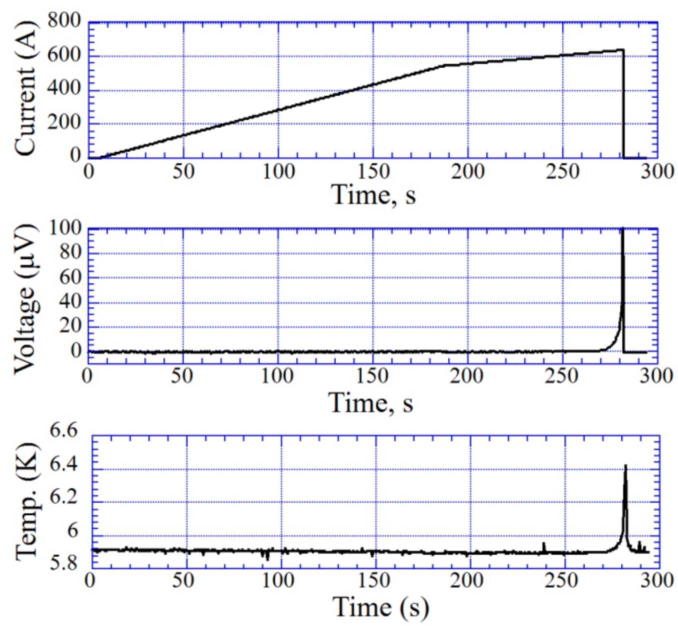

Fig. 5. Measured data of the transport current (top), the voltage (middle), and the temperature (bottom) of the cable sample at B_s= 0 T. n = 192.

V. Evaluation of Critical Current

The critical current of the cable was evaluated with the formulas by the reference [8]. As described in the reference, the *V-I* characteristic of the superconductor is shown by $V = cI^n$, where c is a constant, and the exponent n is an index of the degree of nonlinearity. In the measurements, the voltage criterion level V_c was 8 μV, which was equivalent to 1 μV/cm. The critical current defined by V_c is described as $I_c^{el\ field}$ by Eq. 1. Eq. 2 defines the critical current of the cable as I_c^{offset}. In the following plots, I_c^{offset} is shown as I_{cs}, and the temperature of the sample at I_{cs} is shown as T_{cs}.

$$(dV/dI)_c = nV_c/I_c^{el\ field} \quad (1)$$

$$I_c^{offset} = I_c^{el\ field}\,(1-n^{-1}) = I_{cs} \tag{2}$$

In Figs. 6 and 7, the voltage and temperature changes of the cable with I at B_s=5 T are shown, with the n value and T_{cs}.

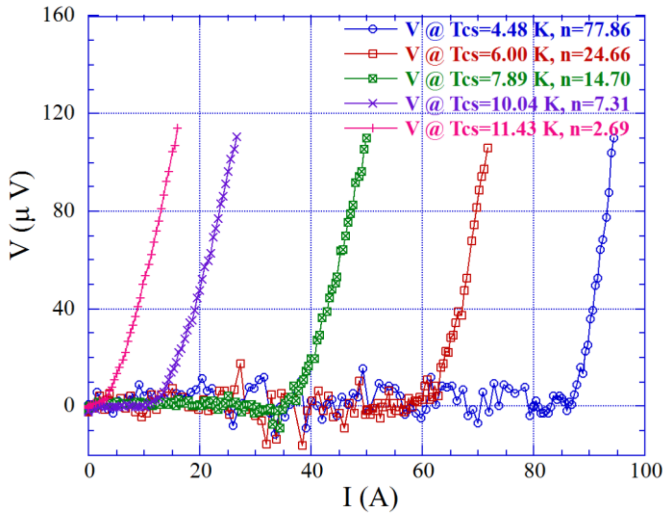

Fig. 6. Measured sample voltage as a function of the current. B_s=5 T.

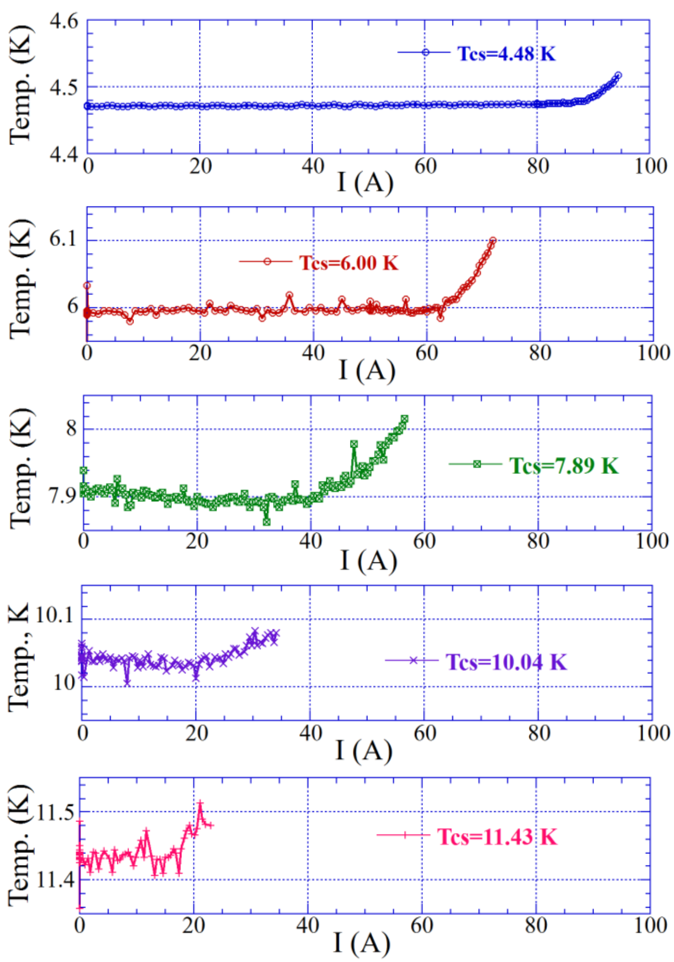

Fig. 7. Measured sample temperature as a function of the current. B_s =5 T.

Under the solenoid field, the measured voltages at 3 A/s fluctuated within ±20 μV compared to the voltage at B_s= 0 T in Fig. 5. The voltage fluctuation was reduced at 1 A/s when the critical current was measured. In Fig. 8, the measured I_{cs} and T_{cs} of the Nb_3Al cable under B_s=0 T, 1 T, 2 T, 3 T, 4 T and 5 T were plotted. From the data, the critical current of the cable at 4 T and 6 K was I_{cs} = 86.4 A, and the current was over the required transport current of 50 A for the corrector magnets, shown in Table III.

The effect of the cabling process with 49 strands on the critical current was evaluated by comparing the non-Cu critical current densities (J_c) of the cable and the single strand wire [4]. The J_c of the single strand at 4.2 K and 4 T was about 3000 A/mm^2, and the J_c of the cable was 2430 A/mm^2. The J_c of the cable was about 80 % of the J_c of the single strand. The difference was due to the strand design or the degradation by the cabling process. To identify the cause, we plan to measure the J_c of the single strand before cabling.

The specific J in the coil of the sextupole magnet is 160 A/mm^2 at 5.5 T and 6 K. From the measured results, the cable J_c at 5.5 T and 6 K was extrapolated to be 327 A/mm^2. For designing the sextupole magnet, the J_c is reduced to 246 A/mm^2 with 4 % degradation in J_c by 0.2 % strain due to the mechanical bend and 85 % cable packing factor. The cable J_c is still higher than the sextupole magnet specification.

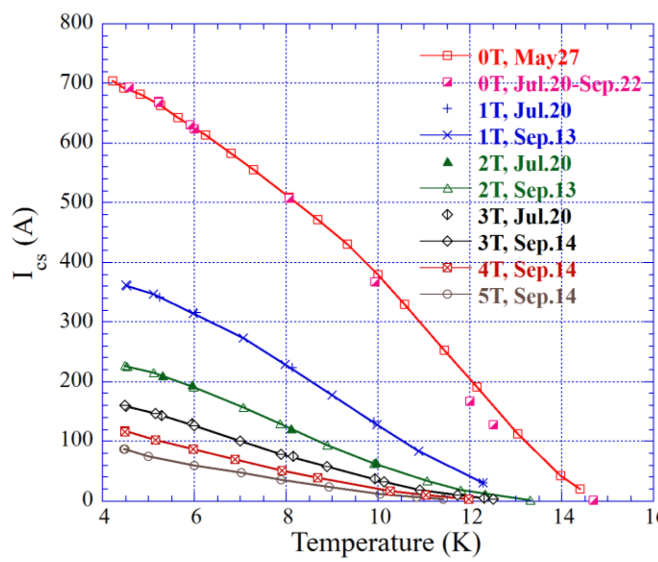

Fig. 8. Temperature and magnetic field dependence of I_{cs} of Nb_3Al cable.

VI. Conclusion

The super fine strand Nb_3Al cable was developed for the R&D of the SuperKEKB superconducting sextupole magnet system. The cable consisted of 49 strands of ϕ 50 μm, which were made of Nb and Al sheets by the jelly-roll method. The temperature and magnetic field dependences of the straight cable on the critical current were measured.

The critical current of the Nb_3Al cable was higher than the design value for the superconducting corrector magnets, and this level of cable performance also indicates the potential for the cable being used for the main sextupole magnet.

As the next step of this R&D, the bending effect of the cable on the critical current is scheduled to be studied.

Acknowledgment

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