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Characteristics of Round and Extracted Strands of Nb_3Al Rutherford Cable

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***Abstract*—Long Nb_3Al strands with copper stabilizer are promising for future high field accelerator magnets. A 1.2 kilometer Nb_3Al strand with Cu stabilizer was fabricated at the National Institute for Materials Science in Japan. Using this strand a 30 meter Cu stabilized Nb_3Al Rutherford cable was made for the first time by a collaboration of NIMS and Fermilab. The Nb_3Al strands extracted from cable with a relatively low packing factor showed almost no J_c degradation. But the extracted strands from the highly compacted cable showed some degradation in both J_c and n value, which may be caused by local separation of the copper stabilizer. Still, its J_c degradation is lower than that of typical Nb_3Sn strands. The current limit due to magnetic instability in low field is about 500 A at 4.2 K. The magnetization of the strands, which was measured with balanced coils at 4.2 K, showed large flux jumps, usually around 1.5 T. This value is much larger than the B_{c2} (4.2 K) of the Nb matrix, which is around 0.4 Tesla. The magnetic instability of the Nb_3Al strand at low field is not completely understood, but it might be explained by the superconducting coupling current through the Nb matrix.**

***Index Terms*— copper stabilizer, extracted strand, magnetization, Nb_3Al strand, RHQT process, Rutherford cable.**

I. INTRODUCTION

A piece of 1.2 kilometer long RHQT Nb_3Al strand has been successfully fabricated with Cu stabilizer at the National Institute for Materials Science (NIMS), in Japan. This was achieved by the recent development of a continuous Cu ion-plating technique that pre-coats a 1 μm thick Cu buffer layer and by the use of a successful high speed electroplating technique [1], [2]. The realization of a long Cu stabilized Nb_3Al round strand is important for its application to the future fusion reactor project and high field accelerator magnets [3]-[5].

In February 2006, a 1.2 kilometer long Cu stabilized Nb_3Al strand was delivered to Fermilab from NIMS, and a 30 meter Rutherford cable was made for the first time in the world. Then the current carrying capacity of the 27 strand Nb_3Al Rutherford cable was tested at 4.3 K and 1.9 K in the field of up to 10 T using FRESCA at CERN [6], [7]. The detailed description of the cable test results is presented at this conference [7]. A small race-track magnet was made at Fermilab and it was tested successfully in October 2006.

In this paper, characteristics of round Nb_3Al strands and extracted Nb_3Al strands of the Rutherford cable are reported. Detailed results on short sample tests and magnetization tests are described.

II. COPPER STABILIZED NB_3AL ROUND STRAND

The Nb/Al precursor strands, ready for a rapid heating-quenching (RHQ) treatment, were manufactured at Hitachi Cable Ltd. by a jelly roll process. Recently, a 2.4 kilometer-long jelly-rolled precursor was successfully produced without breaking [8]. A large multi billet 141 mm in diameter and 450 mm in length was extruded using a hydrostatic extrusion machine with a maximum loading of 4,000 tons.

A jelly-rolled precursor of 1.35 mm in diameter was RHQ treated by a large scale RHQ apparatus at NIMS. The synthesized Nb-Al supersaturated bcc solid solution with 144 filaments proved to be mechanically ductile. In the following step, its diameter was reduced from 1.35 to 0.72 mm, corresponding to area reduction ratio of 71.6 %. The continuous Cu ion-plating is a key technique to obtain a good bonding between the Nb strand surface and the thick

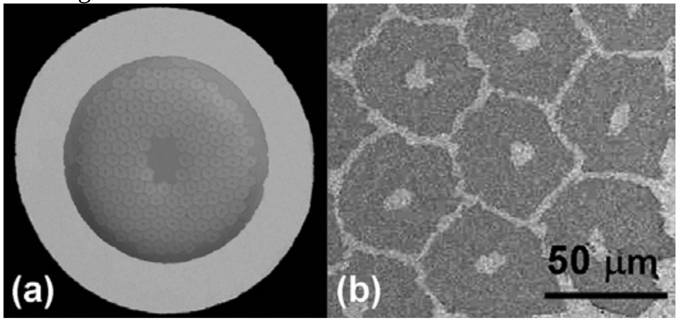

Fig. 1. A cross section of the 1.25 km-long Cu stabilized Nb_3Al round strand.

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TABLE I
SPECIFICATIONS OF CU STABILIZED Nb_3Al ROUND STRAND

Strand ID	F1
Billet No.	HE2457
Precursor fabrication	Jelly roll process
Hydrostatic extruded billet size	141 mm in diameter, 450 mm in length
Total length of precursor	2,400 m (1.35 mm in diameter)
Ratio of Nb/Al laminate	3 (nominal volume)
Strand matrix	Niobium (provided by Tokyo Denkai)
Purity of Nb matrix	99.89 wt% Nb, 0.07 wt% Ta, balance (O, W, N, C, Si, Mo,Ti, Fe)
RRR of Nb matrix	150-200
Normal state resistivity of Nb	7.5×10^{-8} Ω·cm at 9.3 K
Precursor diameter at RHQ	1.35 mm
Area reduction after RHQ	71.6 %
Cu stabilizer fabrication	Ion-planting and electroplating
Final strand outer diameter	1.03 mm
Number of Nb_3Al filament	144
Nb_3Al filament diameter	50 μm (hexagonal)
Nb/Nb_3Al filament ratio	0.645
Cu/non-Cu ratio	1.0
Final piece length	1,250 m

electroplated Cu stabilizer. The detailed description of the copper stabilizer fabrication was published [2]. The final strand diameter was 1.03 mm, after the high speed Cu electroplating (at 2-3 m/h).

A 1.25 km long strand was used for the present Rutherford cable. Fig. 1 (a) shows a cross section of the strand. Physical separation between the Nb barrier and Cu stabilizer was not observed at this stage. The volume fraction of Cu stabilizer is 50 % and its *RRR* is about 200. A geometric filament size, including the pure central Nb, is about 50 μm in diameter as shown in Fig. 1 (b). All filaments are separated by pure Nb barriers with a distance of approximately 3 μm. Table I summarizes the specifications of the present Cu stabilized RHQT-Nb_3Al strand.

III. NB_3AL RUTHERFORD CABLING

A 27-strand Nb_3Al Rutherford cable without a stainless steel core was fabricated using a compact cabling machine at Fermilab. The first 25 meters of the cable was made into a rectangular cable with a low packing factor (PF: 82.5 %), an aspect ratio of about 7. It was 14.2 mm wide and 2.0 mm thick, and had a 15 degree lay angle. An additional 5 meters cable was also made into a rectangular cable but with a higher compaction factor (PF: 89.1 %), an aspect ratio of about 8. It was 14.2 mm wide and 1.8 mm thick, and had a 15 degree lay angle. The cross sectional images are shown in Fig. 2.

With the low compaction cable (LC), a slight separation of copper stabilizer is observed in the edge strands, but there is no separation in the central strands. On the other hand, with the high compaction cable (HC), the copper of central strands is well compressed, but a separation of the copper is observed in the central strands as well as in the edge strands.

(a) Low Compacted Cable (PF: 82.5%)

(b) High Compacted Cable (PF: 89.1%)

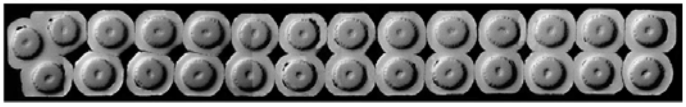

Fig. 2. Cross-sections of rectangular Nb_3Al Rutherford cables. (a) The low compaction cable. (b) The high compaction cable.

All strands were bent with an angle of 150 degrees at the edge of the cable. Therefore the mechanical compressive deformations of the strands were mostly taken by the soft electroplated copper stabilizer, which has a Vicker's hardness of about 60. The Nb-Al supersaturated solid solution filaments proved ductile, but were basically much harder than the stabilizer copper. An area reduction operation of the strand before copper electroplating increased its hardness, resulting in Vicker's hardness of about 420.

IV. CRITICAL CURRENT DENSITY AND N VALUE OF EXTRACTED STRANDS

A virgin round strand and extracted strands from cables were wound on Ti-6Al-4V barrels, and were heat treated at 800 ^{o}C for 15 h in Ar gas flow with a ramp rate of 40 $^{o}C/h$. The Ti alloy end rings were replaced by copper rings, and the ends of the strands were soldered by Sn-Pb alloy. These samples were mounted on the probe by pressure contacts, and the critical current (I_c) measurements were performed in liquid helium (4.2 K) with applied transverse magnetic fields up to 15 T. The I_c were determined by a common resistivity criterion of 10^{-14} Ωm averaged over a 750 mm distance between the voltage taps. The voltage signal versus transport current as a function of applied fields is shown in Fig.3 for the extracted strand of the low compacted cable (LC). Although the tested long specimen had a slight separation of the copper at several places, corresponding to edges of the cable, no resistance appeared up to the critical transition. The non-Cu J_c of the LC extracted strand was obtained as 831.5 A/mm^2 at 15 T at 4.2 K.

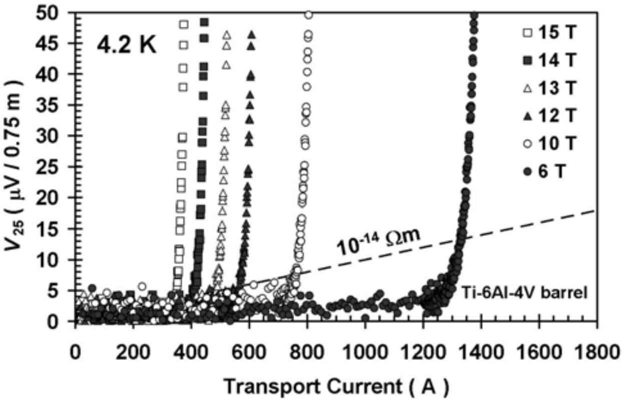

Fig. 3. The voltage signal versus transport current at 4.2 K as a function of applied fields for the extracted strand of the low compacted cable.

Fig. 4 (a) shows the non-Cu J_c as a function of applied field, for a virgin round, LC extracted and HC extracted strands. The normalized J_c (extracted/round) values are shown in Fig. 4 (b). The J_c degradation due to cabling for Nb_3Sn strands generally increases with an increase of a cable packing factor [9]. The extracted Nb_3Al strand with a rather low packing factor (82.5 %) shows almost no J_c degradation (less than 2 %). The J_c degradation of the extracted Nb_3Al strand with a high packing factor of 89.1 % is in the same level as the MJR-Nb_3Sn strand, but it is much lower than that of PIT-Nb_3Sn strand.

Fig. 5 shows the n values of a virgin round strand, LC extracted and HC extracted strands against the applied field value. The n value is very sensitive to the longitudinal homogeneity of the strands, and it apparently decreases by cabling, especially with a high packing factor of 89.1 %. The n value degradation of the LC extracted strand is lower than that of the Nb_3Sn strands. The residual resistivity ratio, *RRR*, of the LC extracted strands is 186 and almost the same for the virgin round strand. The Nb_3Al strands do not have the problems of tin leakage which is frequently observed in Nb_3Sn strand cabling [9]. The degradation of both the J_c and n value for the HC extracted strand may be caused by a local separation of the copper stabilizer as shown in Fig. 2 (b). Table II summarizes the performances of the virgin round, LC extracted and HC extracted Nb_3Al strands.

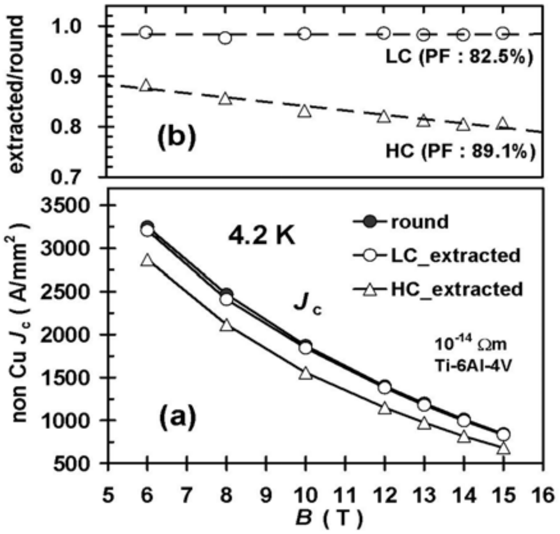

Fig. 4. (a) The non Cu Jc as a function of applied fields, for a virgin round strand, LC extracted and HC extracted strands. (b) The normalized Jc (extracted/round) values are shown.

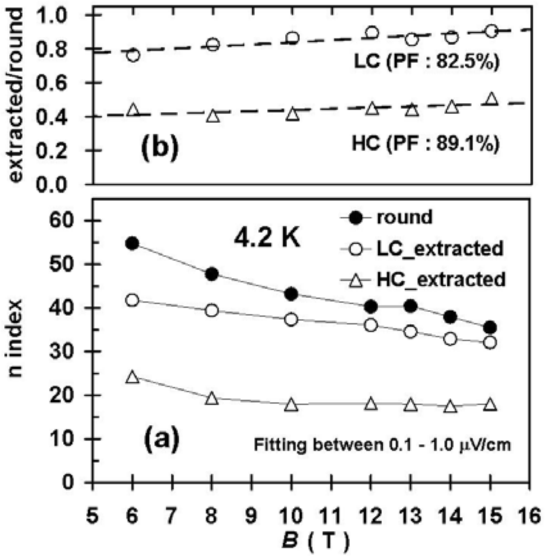

Fig. 5. (a) The n index as a function of applied fields, for a virgin round strand, LC extracted and HC extracted strands. (b) The normalized n values (extracted / round) are shown.

TABLE II

CRITICAL CURRENTS OF CU STABILIZED NB_3AL STRAND

Strand ID	Virgin round	LC extracted	HC extracted
Cable packing factor	-	82.5 %	89.1 %
Heat treatment	15 h at 800 °C (in Ar atmosphere)		
I_c (4.2 K, 12 T)	582.9 A	574.7 A	478.8 A
I_c (4.2 K, 15 T)	351.5 A	346.4 A	283.8 A
non-Cu J_c (4.2 K,12 T)	1,400 A/mm^2	1,380 A/mm^2	1,150 A/mm^2
non-Cu J_c (4.2 K, 15 T)	844.2 A/mm^2	832.0 A/mm^2	681.6 A/mm^2
n value (4.2 K, 12 T)	40.3	36.1	18.2
n value (4.2 K, 15 T)	35.5	32.1	18.0
RRR (20K/300K)	200	186	not measured

V. MAGNETIZATION AND STABILITY AT LOW FIELDS

A. Magnetization Test

The magnetic instabilities of a cable at low field, limits the critical current capacity of a magnet. The magnetization measurements were carried out using two different techniques. One was done with a SQUID magnetometer for a 2.0 mm specimen, and the other with a balanced coil magnetometer for a 900 mm long spirally wound specimen [10]. The cyclic measurement field region is from 0 T to 3 T in both methods.

Magnetization data measured with SQUID at 4.2 K are shown in Fig. 6. Fig.6 (a) shows the reacted specimen with superconducting Nb_3Al filaments, and Fig. 6 (b) shows the unreacted specimen with Nb-Al bcc solid solution filaments which are not superconducting. In Fig. 6 (a), the big flux jumps are seen below 0.6 T. Fig. 6 (b) shows that the signals essentially come from the Nb matrix, since the bcc filaments are non-superconducting at 4.2 K. The magnetization hysteresis is almost zero at 0.57 T, which should be the B_{c2} (4.2 K) of the Nb matrix. This value is slightly larger than the reported B_{c2} (4.2 K) of pure Nb, 0.35 T, but it seems to increase slightly by its purity based on the GLAG theory [11], [12]. The fields, at which big flux jumps are observed, are comparable to the B_{c2} (4.2 K) of the Nb matrix. No flux jumps are usually detected over 1 T by using SQUID for such short specimens. The flux jumps disappear when the temperature is raised to 10 K, and we know that, the Nb_3Al strand with the Ta matrix helps to depress the flux jumps at 4.2 K [13]. These results suggest that the flux jumps may be caused by the huge effective SC filament size though the superconductivity of the Nb matrix.

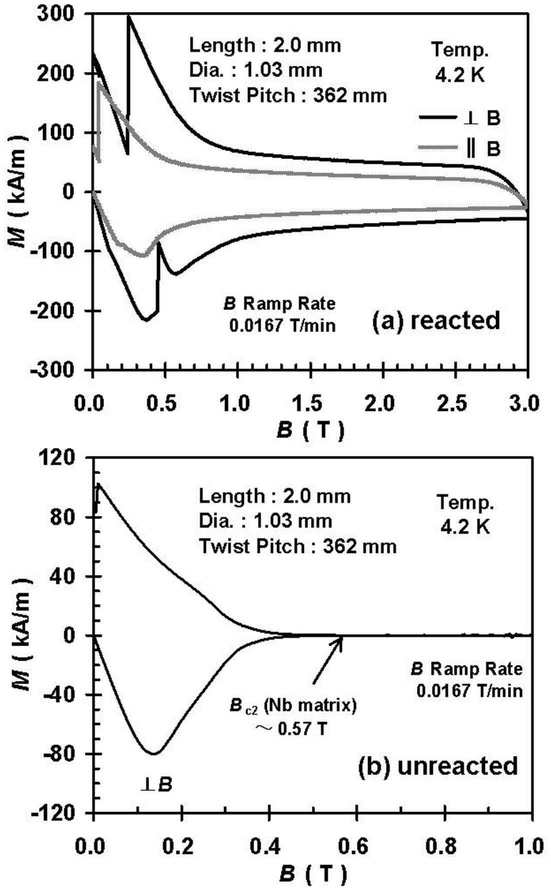

Fig. 6. Magnetization curves tested using the SQUID magnetometer for (a) the reacted Nb_3Al strand, and (b) the unreacted strand.

The 0.9 m long samples are used for the balanced coil magnetometer measurement, and the results are shown in Fig 7 (a) for the unreacted strand, (b) and (c) for the reacted Nb_3Al strands. The B_{c2} of the Nb matrix could be estimated by the balanced coil measurement as well as the SQUID, which is about 0.6 T at 4.2 K as shown in Fig. 7 (a). We found there is apparently a difference between the balanced coil and the SQUID, and the big flux jumps for the reacted specimens usually appeared around 1.5 T, as shown in Fig. 7 (b). The balanced coil measurement might be detecting the effects of a strand twist pitch, because the specimen length is longer than a strand twist pitch. The magnetic field at which flux jumps occur seems not to have a clear dependence on the strand twist pitch, but it changes with the strand twist pitch. This behavior may possibly suggest superconducting filament coupling due to the eddy current loops through the Nb matrix.

Recently, *L. F. Goodrich et. al.* studied this in *RRR* of high purity Nb [14]. It reported that the resistive transition, with a magnetic field in liquid helium, and the high purity of Nb having *RRR* of 414, is completely in the normal state at transverse fields above 1.4 T and at parallel magnetic fields above 2 T. Both of the magnetic fields are apparently above the reported B_{c2} (4.2 K) of pure Nb. This report may indicate that the resistive transition of pure Nb happens at 1-2 T by possibly a magneto-resistance at 4.2 K. It means the pure Nb has very low resistivity below 1-2 T at 4.2 K. However, the Nb matrix in the present Nb_3Al strand may not have enough high purity. The *RRR* value of the present Nb is below 200. In Fig. 7 (c), the flux jumps around 1.5 T at 4.2 K and gradually disappears by increasing the temperature, and completely disappears at 9.3 K which is equivalent to the T_c of pure Nb. This behavior is similar to that of the SQUID measurement [13].

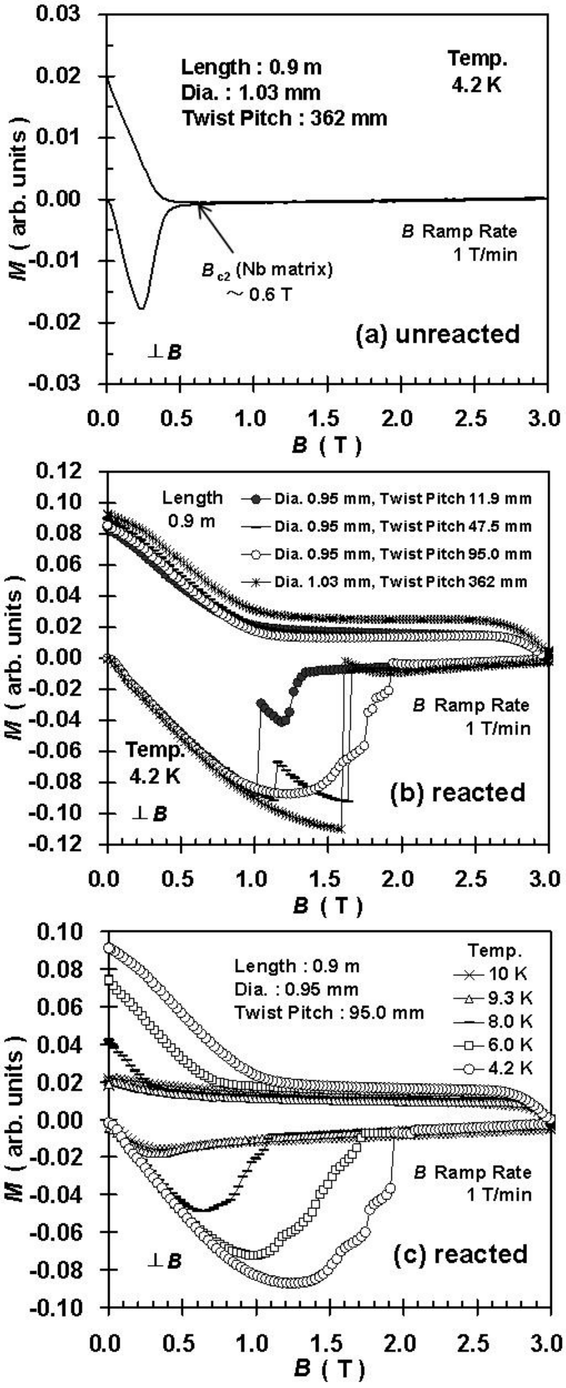

Fig. 7. Magnetization curves tested using the balanced coil magnetometer. (a) is for the unreacted strand, (b) and (c) are for reacted Nb_3Al strands.

B. *Sweeping Field Test*

Fig. 8 shows the stability current (I_s) for the Nb_3Al LC extracted strand as a function of external fields, and the I_c are also plotted to indicate the critical surface. The quench is induced by sweeping the magnetic field from 0 Tesla with a ramp rate of 1 T/min. The minimum I_s was about 520 A, and the strands show no quench fields up to the critical surface for the holding current below 520 A. Fig. 9 shows the magnetic fields, B_q, at which the quench happens, with a holding current of 600 A, as a function of field ramp rate. The B_q seems to decrease with the increasing B ramp rate, but it is still around 1.5 T. The current test for the Nb_3Al cable in self field was performed using the flux pump method, and its maximum quench current at 4.2 K was 27.4 kA [7]. Its maximum self field was estimated as 1.5 T.

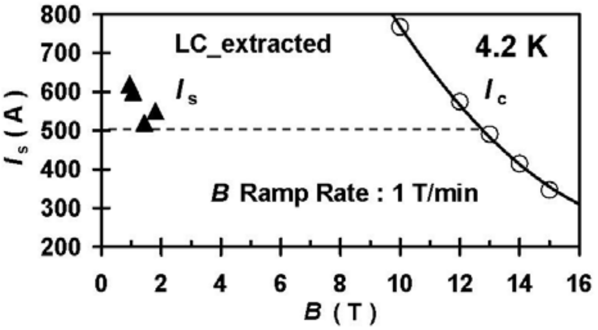

Fig. 8. The quench current values for the LC extracted strand by the sweeping field up from 0 T with ramp rate of 1 T/min.

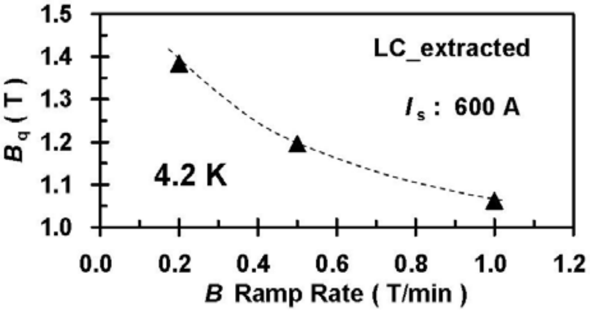

Fig. 9. The ramp rate dependence of the quench field values for the LC extracted strand with a holding current of 600 A.

VI. CONCLUSION

A copper stabilized 1.2 kilometer Nb_3Al round strand was successfully fabricated by NIMS in Japan. Using it, a 30 meter long Cu stabilized Nb_3Al Rutherford cable was successfully made also for the first time in the world with the collaboration of NIMS and Fermilab.

We tested the Cu stabilized Nb_3Al strands, round and extracted, extensively in their current capacity, magnetization, as well as stability. The Nb_3Al extracted strands from the Rutherford cable with relatively low packing factor show almost no $\boldsymbol{J_c}$ degradation. The LC strand was current limited to values of less than 500 A due to low field instabilities.

The balanced coil measurements at 4.2 K shows the flux jumps of the Nb_3Al strands usually appear around 1.5 T, which is much larger than B_{c2} (4.2 K) of the Nb matrix. The instability in low field of the present Nb_3Al strand is possibly caused by superconducting filament coupling and the eddy current loops through the Nb matrix. This problem will be studied further.

In this work, we were able to demonstrate that Cu stabilized Nb_3Al strand can be a viable conductor, comparable to Nb_3Sn at high fields, although improvements in low field stability and overall J_e are needed.

Long Cu stabilized Nb_3Al strands are very promising for the application to future high field accelerator magnets. We think we must stimulate its application to the future high field accelerator magnets as well in other fields.

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