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Magnetization Anomaly of Nb_3Al Strands and Instability of Nb_3Al Rutherford Cables

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***Abstract*— Using a Cu stabilized Nb_3Al strand with Nb matrix, a 30 meter long Nb_3Al Rutherford cable was made by a collaboration of Fermilab and NIMS. Recently the strand and cable were tested. In both cases instability was observed at around 1.5 Tesla. The magnetization of this Nb_3Al strand was measured first using a balanced coil magnetometer at 4.2 K. Strands showed an anomalously large magnetization behavior around at 1.6 T, which is much higher than the usual B_{c2} ~0.5 Tesla (4.2 K) of Nb matrix. This result is compared with the magnetization data of short strand samples using a SQUID magnetometer, in which a flux-jump signal was observed at 0.5 Tesla, but not at higher field. As a possible explanation for this magnetization anomaly, the interfilament coupling through the thin Nb films in the strands is suggested. The instability problem observed in low field tests of the Nb_3Al Rutherford cables is attributed to this effect.**

***Index Terms*— Instability, Magnetization of Nb, Nb_3Al, Superconductor Strand**

I. INTRODUCTION

RECENTLY stabilized Nb_3Al strands were made by electroplating copper at National Institute for Material Sciences in Japan. Its detailed characteristic parameters and production process are reported earlier [1]. The cross-section of the strand, called F1 is shown in Fig. 1a, with an accompanying detailed picture of subelments in Fig.1b. In Fig 1a the central Nb core about 100 µm is shown and the in Fig 1b we can see each subelement has a small central Nb core and each subelement is separated by about 3 µm layer of Nb.

The content of the Nb is 20 %, which is a large fraction of the strand. The detailed characteristics of this F1 round and extracted strands is reported in this conference [2]. Its major parameters are listed in the Table I. During strand test of magnetization we observed very large flux jump like behavior.

Using 1 km of F1 Nb_3Al strand we made about 30 m long Rutherford cable of 27 strands, including a 25 m cable of low compaction (82.5%). Its cross section is shown in Fig. 2. The specifications are listed in Table II.

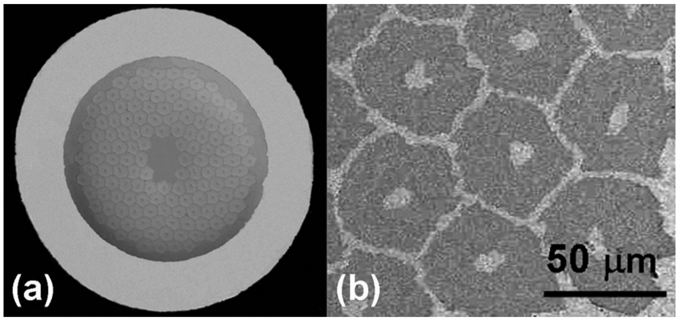

Fig. 1. A cross section of 1.25 km-long Cu stabilized Nb_3Al round strand.

TABLE I
SPECIFICATIONS OF CU STABILIZED NB_3AL ROUND STRAND: F1

Strand ID	F1
Precursor fabrication	Jelly roll process
Ratio of Nb/Al laminate	3 (nominal volume)
Strand matrix	Nb (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
Cu stabilizer fabrication	Ion-plating and electroplating
Final strand outer diameter	1.03 mm
Twist Pitch	362 mm
Number of Nb_3Al filament	144
Nb_3Al filament diameter	50 µm (hexagonal)
Nb between Nb_3Al filaments	3 µm
Anomalous Flux Jump	At 1.6 Tesla at 4.2 K
Nb/Nb_3Al filament ratio	0.645
Cu/non-Cu ratio	1.0
Ic (4.2 K, 12 T / 15 T)	582.9 A / 351.5 A
non-Cu Jc (4.2 K, 12T / 15 T)	1,400 / 844.2 A/mm^2
RRR of Cu	200

TABLE II
SPECIFICATIONS OF CU STABILIZED NB_3AL RUTHERFORD CABLE: F1-CABLE

No. of F1 Strands	27
Size	14.2 mm x 2.0 mm, Rectangular
Compaction Factor	82.5 % (Low Compaction)
Iq (10 T)	17.8 kA (Ramp rate 2 kA/s) [3]

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A pair of 173.5 cm long Nb$_3$Al Rutherford cables was tested at FRESCA facility of CERN with high transport current in the high field dipole magnet up to 10 Tesla at 4.3 and 1.9 K, and the cable test data are reported in this conference [3]. In the external field up to 9 Tesla, it seems the quenches started near the splices in the low field region. In this paper we will describe the possible causes of these quenches.

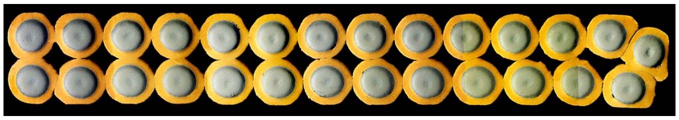

Fig. 2. Cross-section of a rectangular Nb$_3$Al Rutherford cable with a low compaction factor 82.5 %. The F1 strands were used. 14.2 mm x 2.0mm

II. MAGNETIZATION OF NB$_3$AL STRANDS

A. Nb$_3$Al strands with Different Matrix

The RHQT Nb$_3$Al strands with Ta and Nb matrix have been produced in the past, and their magnetizations were measured and reported [4]. Their magnetization curves for short samples, which were measured with a SQUID magnetometer at stationary condition, are shown in Fig. 3 [4]. The magnetization curve of a Nb$_3$Al strand with Nb matrix, similar to the present F1 strand is shown in Fig. 3a, and that of a Nb$_3$Al strand with Ta matrix is shown in Fig. 3b. It is clear that the strand with Nb matrix has quite big flux jumps in low field region below 0.5 Tesla. The Tc of Ta is 4.5 K and that of Nb is 9.25 K. Based on this knowledge, the next strand for the present project is being considered to be made with Ta matrix.

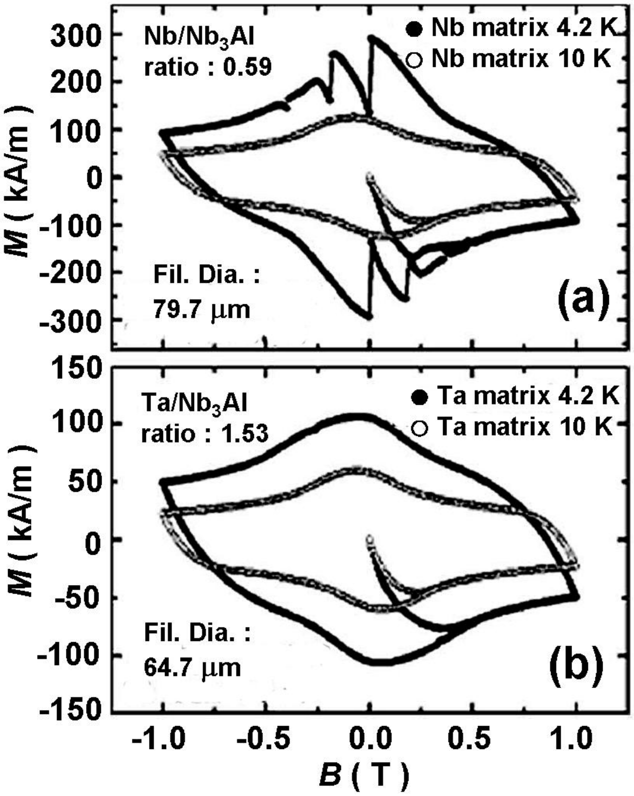

Fig. 3. Magnetization curves of (a) Nb matrix and (b) Ta matrix RHQT Nb$_3$Al strands at 4.2 K and 10 K measured at NIMS with a SQUID magnetometer [4].

B. Magnetization curve of F1 strands

The magnetization curve of a 900 mm F1 Nb$_3$Al strand is shown in Fig. 4 [2]. It was measured using a balanced coil magnetometer at Fermilab [5]. The induced signal in a sample detection coil at sweeping speed of 1 Tesla/min is integrated with a home made integrator. The field sweep is done from 0 to 3 Tesla twice in sequence. This first loop has a big flux-jump like step at 1.6 Tesla, but not in the second loop.

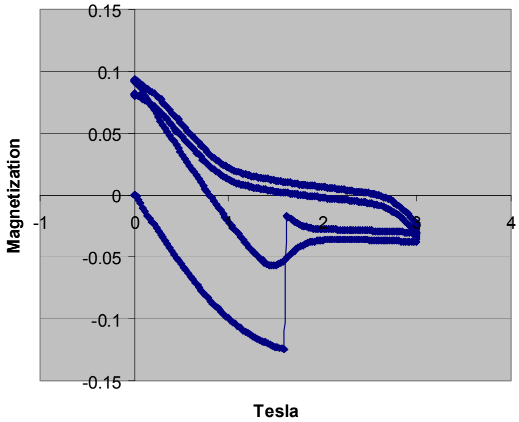

Fig. 4. Magnetization curve observed with a balanced coil magnetometer. Abnormally large magnetization loop and a big flux-jump like step are observed at 1.6 Tesla, which occurs at much higher field than the Bc2 value (about 0.5 Tesla) of Nb. There is no abnormally big jump in the second loop.

C. Simple consideration on Nb$_3$Al strands

The Bc2 of Nb is about 0.4 to 0.6 Tesla depending on its quality. It was thought that the magnetization curve of Nb matrix Nb$_3$Al strand like F1 strand should be like Fig. 3a, even when measured with our device, and any flux jump should occur at less than 0.6 Tesla.

We have been developing a computer simulation on magnetization curves using commercially available program, ANSYS. Its animation program is reported in this conference [6]. If the Nb is superconducting in low external field, we should expect the flux distribution as shown in Fig. 5a, where there is no flux penetration into the core of Cu stabilized Nb$_3$Al strand.

When the external field exceeds Bc2, about 0.5 Tesla, the flux should be distributed as shown in Fig.5b, where the external field saturated the Nb area at complete stationary field.

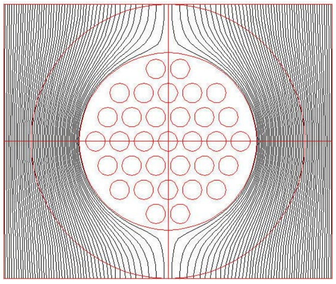

Fig. 5a. Flux line pattern in the Cu stabilized Nb$_3$Al strand, when the Nb is superconducting in a low external field. This is simulated with ANSYS [6].

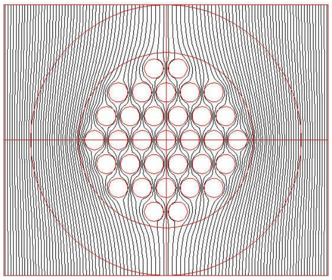

Fig. 5b. Flux line pattern in the Cu stabilized Nb_3Al strand when the external field is above Bc_2 of Nb, namely above 0.6 Tesla and in a really stationary field. Nb is not superconducting. This is simulated with ANSYS [6].

D. *Eddy Current Effect in Nb_3Al strand due to Interfilament Coupling*

Even at an external magnetic field beyond Bc2 of Nb (~0.5 Tesla), it is estimated that the eddy current due to interfilament coupling is preventing the external flux to get completely into the inside part of the strand, if the magnetic field is changed even at slow rate.

To see this effect, we measured the magnetization curves of the unreacted Nb_3Al strands using both the SQUID and the balanced coil methods.

We observed neither an anomalously large magnetization loop nor a huge flux-jump like step with unreacted F1 Nb_3Al strand samples with the balanced coil magnetometer as shown in Fig. 6a, neither with the SQUID data. These data show only the magnetization curve of Nb, indicating a clear Bc2 point at 0.6 Tesla.

This suggests the existence of the interfilament coupling with a heat treated F1 Nb_3Al strand. As can be seen from Fig. 1b, Nb foils between filaments are about 3 μm thick, so proximity effect might be involved.

E. *Interfilament Coupling and Twist-pitch Length*

As the present F1 Nb_3Al strand has a rather long twist pitch length of 362 mm, we made samples with different pitch length, and tested its effect. The results are shown in Fig. 6b for the twist pitch length of 362, 95, 47.5, 11.9 mm. In general, there are still unstable big flux-jumps above 1 Tesla, but the anomaly is becoming smaller with shorter twist pitch. We can observe some twist pitch effect. Flux jump point comes down to 1.0 Tesla with the shortest twist pitch of 11.9 mm. With 95 mm twist pitch strand, there is a rather smooth change. These cases need more studies.

F. *Effect of Nb and Nb_3Al at different Temperatures*

In order to see the temperature effect on the interfilament coupling, the balanced coil measurement was done at different temperatures. The test results are shown in Fig. 6c. As expected the interfilament coupling is reduced at higher temperature and disappeared at 9.3 and 10 K, as the Tc of the Nb is 9.2 K. This shows the big bump is clearly related to the transition of Nb and also may be related to the Jc reduction of the screening current in the reacted Nb_3Al strand due to higher temperature.

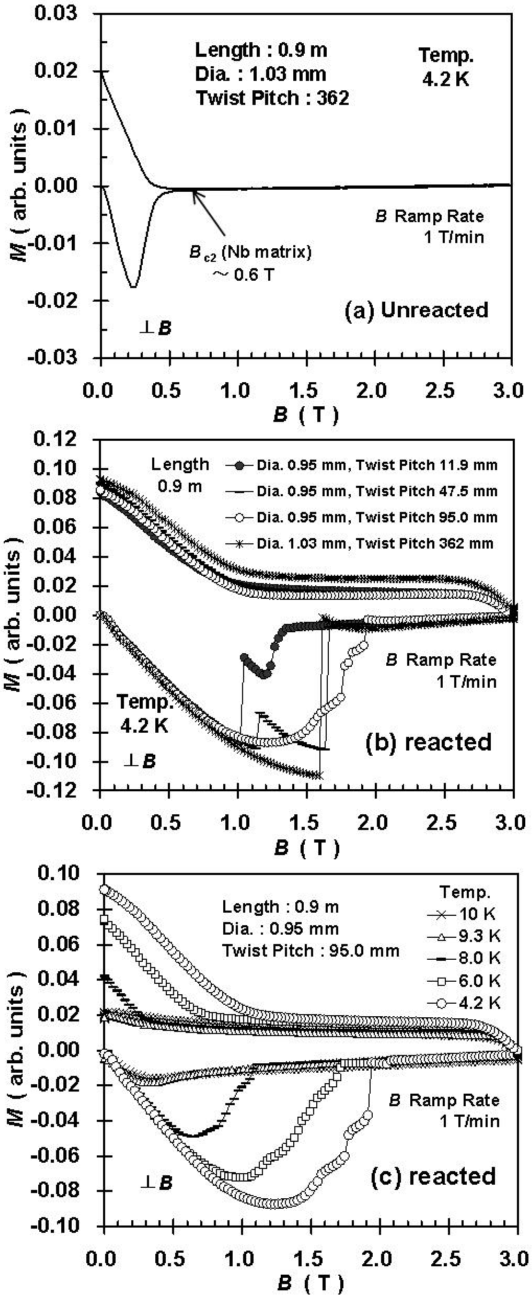

Fig. 6. Magnetization loops measured with the balanced coil magnetometer. Fig. 6a Loop for an unreacted F1 Nb_3Al strand. Fig. 6b Twist pitch effect of the reacted samples. Fig. 6c. Temperature dependence of the reacted sample.

G. *Full Flux Penetration into Nb and generating unstable and abnormally large Disturbance*

We can assume the Nb becomes non superconducting at the field value about 1 Tesla due to the resistive transition of Nb. Then the external magnetic flux penetrates into all of the Nb space, as shown in Fig. 5b. During this transition the interfilament coupling current will generate a disturbance in the strand, at around 1.6 Tesla, as shown in Fig. 4.

In reality, the whole system is dynamically changing so more elaborate considerations will be needed.

III. INSTABILITY OF Nb_3Al RUTHERFORD CABLE AT LOW FIELD REGION

A spliced pair of Nb_3Al Rutherford cables 173.5 cm long each, was tested at the FRESCA facility of CERN with high transport current up to 10 Tesla at 4.3 and 1.9 K [3]. The relative positions of the splices are shown in Fig. 7 together with the applied FRESCA external field distribution. With this setup, always some end area of the cables is excited only up to 1 to 2 Tesla, regardless of the maximum excitation field value. The cables are made of F1 Nb_3Al strands, which tend to have flux jumps at 1.6 Tesla.

The quench data of the tested cables are shown in Fig. 8. In this figure the self-field up to 1 Tesla is added for the value of B. During the test many quenches started at or near the splices. Some of them started at the spices, but all of data between 1.5 to 9 Tesla started near the splices. It could be explained that when the total field reaches at 1.5 Tesla near the splices, that part of the cable starts a quench. Therefore we can conclude there is instability problem in low field region with this Nb rich Nb_3Al cable.

Above 9 Tesla all data, both at 4.3 K and 1.9 K, with ramp rate below 500 A/s quenched at or near the splices. In the Fig. 8, they are inside the region marked as "splice quench". At faster ramp rate the cable quenched in the high field region, as marked "cable quench" in Fig. 8 [3].

At zero to 1 Tesla external field tests, many quenches started in the middle of the cable as well as near splices, as also shown in Fig. 8.

IV. CONCLUSION

As can be seen in Fig.1, there are 20 % of pure Nb in this strand, and many Nb cores and films are imbedded close to Nb_3Al filaments. Therefore we should expect coupling between Nb_3Al filaments and pure Nb matrix.

We observed the abnormally large magnetization of the present Nb matrix Nb_3Al strand, F1, and its accompanying large flux-jump like steps around 1.6 Tesla much beyond B_{c2} of Nb. We explained that these phenomena are related to the interfilament coupling current though the Nb material, using a couple of experimental data. But we still need to work out the detailed mechanism how and which part of Nb material are contributing to generate the anomaly.

Experimentally we found the present Nb_3Al Rutherford cables made of F1 strands quench prematurely at or near the splices around 1.5 Tesla. This instability of the Nb_3Al Rutherford cable in the low field region can be explained with the anomaly of the Nb_3Al strand at 1.5 Tesla, by assuming that the anomaly of F1 strands also could happen with a transport current. We still need further study on this problem too.

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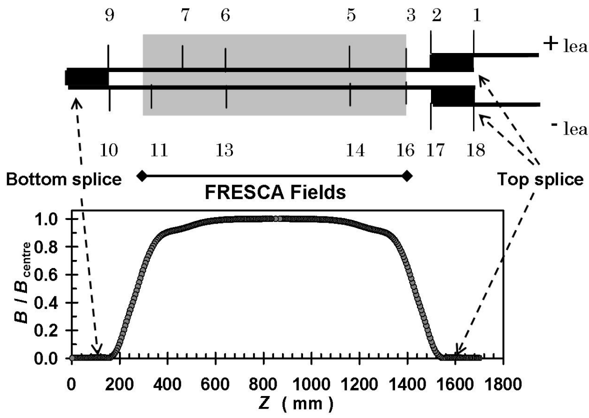

Fig. 7. Relative positions of splices in the external field distribution. Near the splices, there is always field region around 1.5 Tesla regardless of the external field. The positions of the voltage taps 1 to 18 on the test cable are also shown. These taps were used to measure the quench velocities.

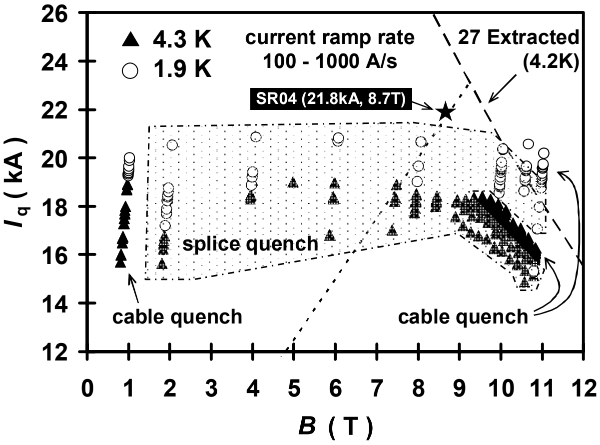

Fig. 8. Quench current values of the cable test at CERN at 4.3 K and 1.9 K are shown. Also in this figure, the load line for SR04 magnet and its highest quench value at 3.95 K are shown for comparison [3].

REFERENCES

[1] A. Kikuchi, K. Tagawa, M. Kobayashi, Y. Iijima, T. Takeuchi, and H. Kitaguchi, "Fabrication of Cu Stabilizer into Long-Length RHQT-Processed Nb_3Al Round Wire," *IEEE Trans. Appl. Supercond.*, vol. 16, pp. 1224-1227, 2006.

[2] A. Kikuchi, R. Yamada, G. Ambrosio, N. Andreev, E. Barzi, C. Cooper, Y. Iijima, M. Kobayashi, H. Kitaguchi, S. Nimori, M. Lamm, K. Tagawa, T. Takeuchi, K. Tsuchiya, D. Turrioni, M. Wake and V.A. Zlobin "Characteristics of Round and Extracted Strands of Nb_3Al Rutherford Cable", presented in this conference.

[3] R. Yamada, A. Kikuchi, G. Ambrosio, N. Andreev, E. Barzi, C. Cooper, S. Feher, V. Kashikin, M. Lamm, I.Novitski, T. Takeuchi, D. Turrioni, A. Verweij, M. Wake, G. Willering and A.V. Zlobin, "Feasibility Study of Nb_3Al Rutherford Cable for High Field Accelerator Magnet Application", presented in this conference.

[4] T. Tekeuchi, N. Tatsumi, S. Nimori, H. Kitaguchi, N. Banno, Y. Iijima, A. Kikuchi, and K. Inoue, "Manufacture and Superconductivity of Tantalum Matrix RHQT Processed Nb_3Al superconductors," *IEEE Trans. Appl. Supercond.*, vol. 15, pp. 3372-3375, 2005.

[5] C. Boffo and E. Barzi, "Magnetization Measurements at the SSTF", FNAL technical report, TD-99-036, 1999.

[6] M. Wake and R. Yamada, "FEM Calculation of Magnetization Process in a Multi-Filamentary Superconductor", presented in this conference.