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Feasibility Study of Nb_3Al Rutherford Cable for High Field Accelerator Magnet Application

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***Abstract*— Feasibility study of Cu stabilized Nb_3Al strand and Rutherford cable for the application to high field accelerator magnets are being done at Fermilab in collaboration with NIMS. The Nb_3Al strand, which was developed and manufactured at NIMS in Japan, has a non-copper Jc of about 844 A/mm^2 at 15 Tesla at 4.2 K, a copper content of 50 %, and filament size of about 50 microns. Rutherford cables with 27 Nb_3Al strands of 1.03 mm diameter were fabricated and tested. Quench tests on a short cable were done to study its stability with only its self field, utilizing a high current transformer. A pair of 2 meter long Nb_3Al cables was tested extensively at CERN at 4.3 and 1.9 K up to 11 Tesla including its self field with a high transport current of 20.2 kA. In the low field test we observed instability near splices and in the central region. This is related to the flux-jump like behavior, because of excessive amount of Nb in the Nb_3Al strand. There is possibility that the Nb in Nb_3Al can cause instability below 2 Tesla field regions. We need further investigation on this problem. Above 8 Tesla, we observed quenches near the critical surface at fast ramp rate from 1000 to 3000 A/sec, with quench velocity over 100 m/sec. A small racetrack magnet was made using a 14 m of Rutherford cable and successfully tested up to 21.8 kA, corresponding to 8.7 T.**

***Index Terms*— Nb_3Al, Rutherford Cable, Superconductivity**

I. Introduction

THE Nb_3Al strand has been known to withstand higher stress than Nb_3Sn strands, but its application has been limited, because it was difficult to make a long Cu stabilized Nb_3Al strand. Recently stabilized Nb_3Al strands were made by electroplating copper at the National Institute of Material Sciences in Japan, and stabilized Nb_3Al strands over 1 km were made. The detailed characteristic parameters and production process for this strand are reported [1].

Recently Nb_3Al strands have been used in fusion projects in the field range of 13 Tesla as CICC cables [2], and are being tested for the possible application as the inner coil of the 1 GHz NMR [3]. It is also being considered for use in accelerator magnets [4]-[5].

We have made two different Rutherford cables utilizing two different Cu stabilized Nb_3Al strands. In this paper the Nb_3Al strand, called F1, is briefly described and the test results of Rutherford cables are presented.

II. RHQT (Rapid-Heating Quenching and Transformation) Nb_3Al Strand

The present Nb_3Al strand is made by the 'Jelly Roll' method. The alternate foils of Nb and Al (composition: 75at%Nb-25at%Al) are wrapped around a Nb rod, and on top of it another Nb foil is wrapped. 144 monofilaments are stacked around the central Nb core and placed into a Nb can making a billet. This assembly is hydrostatically drawn into a thin multifilament wire [1].

The Nb/Al multifilament wire is Ohmic-heated rapidly to a very high temperature (~1900°C), and then quenched into a molten Gallium bath at ~50°C. The ductility of the whole composite is ensured to make a Rutherford cable. The cold reduction of its diameter is essential to increase its eventual Jc value. Next the surface of the precursor strand is Cu ion-plated under vacuum, and electroplated with Cu to add the thick copper stabilizer [1]. The cross section of the 1.03 mm diameter strand is shown in Fig. 1.

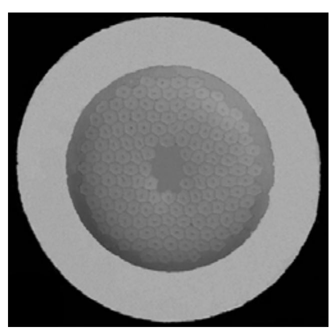

Fig. 1. 1.03 mm Nb_3Al strand: F1.

After the Rutherford cabling operation, the strand is transformed into A15 phase by heating at 800°C for only 15 hours.

The non-copper J_c of 844 A/mm^2 at 15 Tesla at 4.2 K is achieved at an I_c of 352 A. It is expected I_c will be 420 A at 15 Tesla at 1.8 K. The Nb matrix/Nb_3Al ratio is 0.6 and the Cu/non-Cu ratio is 1.04. The detailed description of the tested strand's characteristics is presented at this conference [6].

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III. Nb_3Al RUTHERFORD CABLING

Using 1 km of F1 Nb_3Al strand we made about 30 meters of 27 strand Rutherford cable, including a 25 meter cable of low compaction (82.5 %) cable. Its cross section is shown in Fig. 2. The cable is of rectangular shape, 14.2 mm wide, 2.0 mm high, and with 15 degree lay angle. In this cable there is a slight separation of copper from the Nb_3Al core at the edge strands. We also made 5 meters of Rutherford cable with high compaction of 89.1 %. At this compaction the central strands' copper is well compressed, but the edge strands have their stabilizing copper more squashed. In general the Nb_3Al cores have kept almost the original round shape, because of its Vicker's hardness of 420. But the electroplated soft copper with a Vicker's number of only 60 took most of the deformation. We did not make a key-stoned cable, because we expected excessive deformation in the copper.

Fig. 2. Cross-section of rectangular Nb_3Al Rutherford cable with low compaction factor 82.5 %. The F1 strands were used. 14.2 mm x 2.0mm.

At the compaction rate of 82.5 %, there is no degradation in Ic values, but we observed some degradation with higher compacted cable due to some detachment of the electroplated copper [6].

IV. CABLE TEST WITH FLUX-PUMP AT SELF-FIELD

A two foot Rutherford cable of low compaction factor was tested at 4.2 K with the flux pump method with full current as described in the previous report [7]. Its training curve is shown in Fig. 3, where the maximum achieved current in the Nb_3Al cable was 27.4 kA, corresponding to 1015 A/strand. This number proved there is no excessive disturbance in the low field region. We estimate its maximum self field is 1.5 Tesla.

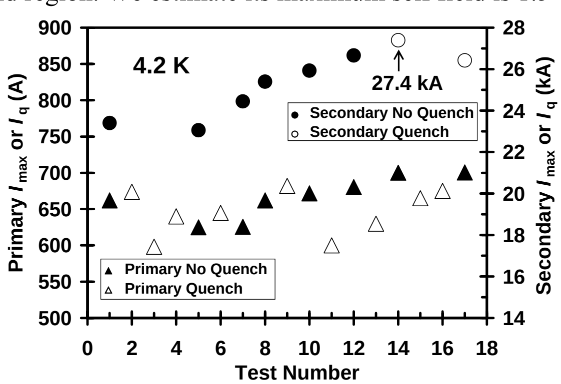

Fig. 3. Flux-pump test results for F1 Nb_3Al Rutherford cable. The flux pump was working near its capacity, quenching in the primary many times.

V. CABLE TEST WITH TRANSPORT CURRENT AT CERN

A pair of low compaction factor Nb_3Al Rutherford cables of 173.5 cm length were tested at the 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 [8]. The relative position of the voltage taps are shown in Fig. 4. In the present test we set the self-field to add to the external dipole field, resulting in additional 0.9 Tesla added. We followed the same test procedure, which was carried out last year with PIT Rutherford cable [9].

The Rutherford cables are wrapped with S-glass tape with 20 % overlapping, and hardened with Ceramic binder. The pair of the cables was stacked without any further insulation between them, and was sandwiched with similarly insulated dummy cables. And a 5 mil Kapton sheet was placed on both sides. They were incased in the sample holder and epoxy impregnated under a pressure of 40 MPa.

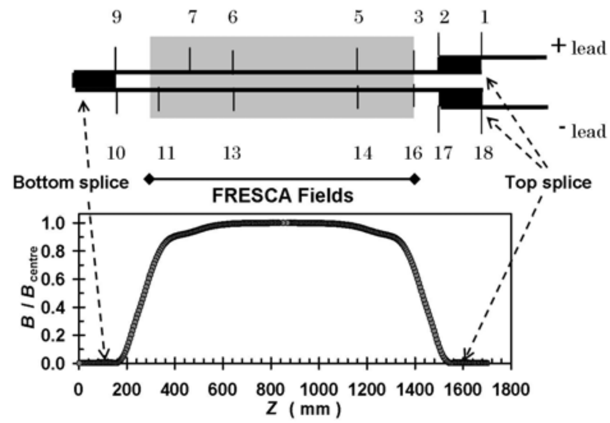

Fig. 4. Rutherford Nb_3Al test setup at FRECCA of CERN. The relative position of the taps, splices and the external field distribution is shown.

First the cable was tested at 4.3 K with the external field up to 7 Tesla, and later tested further up to 10 Tesla with the dipole magnet cooled at 1.9 K. The test results of quench current are shown in Fig. 5, where the self field of the transport current is included.

In these measurements, the external field was set first and the transport current was increased until the cable quenched.

1) Cable Test at 4.3 K below 7 Tesla

Up to 7 Tesla, except at 0 Tesla, a quench always started at the splices, or near the splices. Even when we increased the ramp rate of the transport current up to 2000 A/s, either the bottom splice connecting the pair of the Nb_3Al cables, or top splices joining a Nb_3Al cable and a NbTi lead cable, heated up first. The resistances of these splices were measured to be in the order of 1 nano-Ω. We need to improve the design of these joints for better cooling in future testing.

But it could be logical to assume that the quench is started at the low field region next to the joint region as shown in Fig. 4, due to instability caused by the flux-jump like behavior of the excessive Nb in the Nb_3Al strand. This effect is extensively explained in the accompanying papers for the Nb_3Al strand in this conference [6] and [10].

2) Cable Test at 4.3 K at Zero External Field

At 0 Tesla external excitation, corresponding to data points around 1 Tesla in Fig. 5, we observed many spikes and quenches started in the central cable region in some cases. These may be related to low field flux-jump like instability of the Nb in the Nb_3Al strands around 1 to 1.5 Tesla [6] and [10].

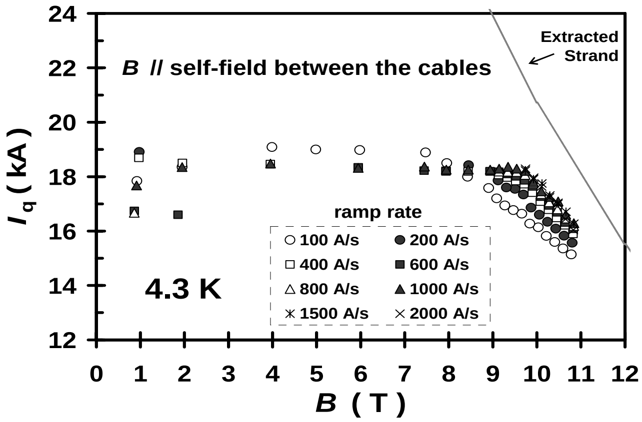

Fig. 5. Nb_3Al cable test data at 4.3 K done with external field at CERN.

3) Cable Test at 4.3 K above 9 Tesla up to 11 Tesla

In this field region the cable quenched near the splices at the ramp rate up to 400 A/s. At higher ramp rate from 600 up to 3000 A/s, the cable started its quenches in the higher central field region, not at the splices. These test data points are also shown in Fig. 5.

In this region the quench current values are lined up in parallel to the short sample limit curve, which are derived from the extracted short sample date multiplied with the strand number of 27. There is about 10 to 15 % overall degradation over the extracted values, which we can expect from the thermal insulation in the present probe holder.

The ramp rate dependency at different external fields in this region is shown in Fig. 6. As we can see the quench current values increase up to 2000 A/s, and then decrease.

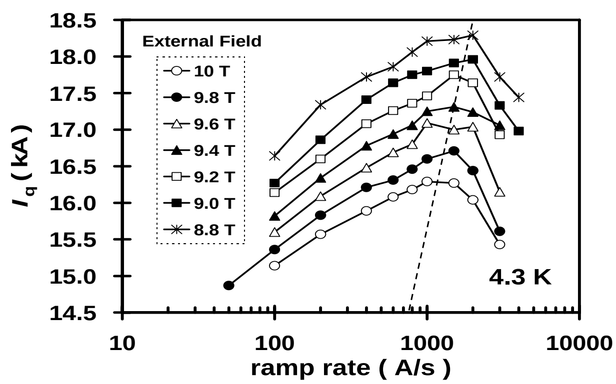

Fig. 6. Ramp rate dependency of quench current values at high field region.

4) Quench Velocity in the 8 to 11 Tesla Region

The typical voltage tap signals for this region are shown in Fig. 7 for the quench current at 10.8 Tesla. In this case, it can be seen that the initial quench started at 1ms somewhere in the region (11,13) in the –lead side. At 2.2 ms, the quench front reached at point 13, and at 6.8 ms it reached at point 14. With a distance of 500 mm, we can calculate the quench velocity is 109 m/s. Also it can be seen the quench propagated to the +lead side through the insulation in 0.8 ms, and it propagated along the cable.

The calculated quench velocity from the data is shown in Fig. 8. Also in this figure, data points at 0 Tesla external field are shown at 1 Tesla because of the self field. And 1 Tesla external field data points are also shown at 2 Tesla.

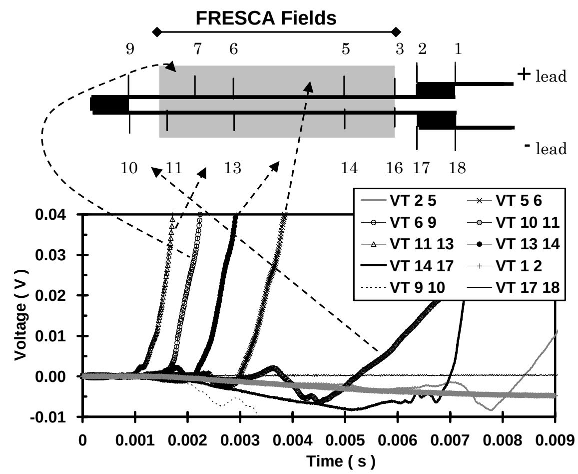

Fig. 7. Quench behaviors and quench velocity determination at 10.8 T at 4.3 K. Ramp rate at 1000 A/s. Iq = 15.81 kA. Vq = 109 m/s for >1.2 ms.

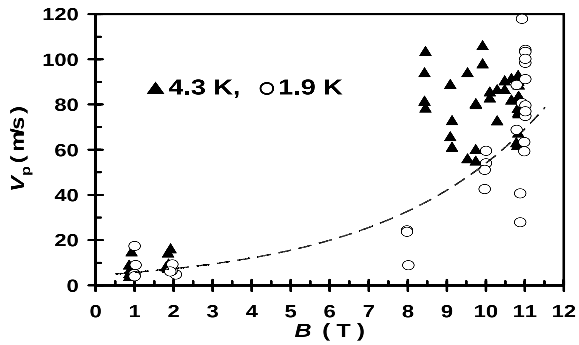

Fig. 8. Calculated quench velocity values above 8 Tesla and below 2 Tesla for both 4.3 and 1.9 K are shown.

5) Quench Current Test at 1.9 K

The cable was tested at 1.9 K at the ramp rate of 100 to 1000 A/s. In general, the quench current at 1.9 K is higher than the value at 4.3 K, as is shown in Fig. 9. The calculated quench velocities at 1.9 K are also shown in Fig. 8.

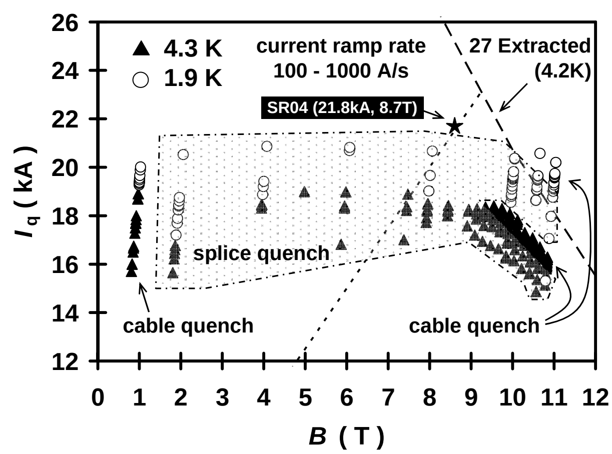

Fig. 9. Quench current values of the cable test at CERN at 1.9 K are shown together with values at 4.3K. Also in this figure, the load line for SR04 magnet and its highest quench value at 3.95 K are shown for comparison.

VI. Instability at Low Field Region

Extensive description about the instability of the Nb_3Al strand at the low field region from 1 to 2 Tesla is given in other papers [6] and [10]. It could be concluded the excessive amount about 20 % of Nb in the strand is the cause. The Bc2 of Nb is about 0.4 to 0.6 Tesla, but the interstrand coupling and the resistive transition of Nb may be causing its instability in this field region.

VII. Small Racetrack Coil – SR04

With a 14 m long Nb_3Al Rutherford cable we made the coil of the small magnet SR04, which is shown in Fig. 10, similar to the previous magnet SR03. These magnets have two-layer small racetrack coils which are connected in the opposite direction and stacked tight together [11].

In October 2006, the magnet SR04 was successfully tested up to 21.8 kA, corresponding to 8.7 Tesla at the inner edges of the coil blocks, without significant training. Its load line and the highest current point are shown in Fig. 9. Its detailed test data will be reported later.

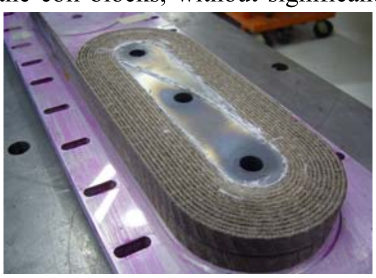

Fig.10. The wound and heat treated coil of the SR04 magnet before epoxying.

VIII. Further Improvements

Recent improvements in the current density of the Nb_3Al strand is impressive, but we still want improvement and to have it further increased well above Jc =1000 A/mm^2 at 15 Tesla at 4.2 K. In order to make a better Rutherford cable, we should like to increase the compaction factor. The electroplating of copper on the Nb_3Al precursor was successfully achieved, but we still have to achieve much stronger bonding between the copper and the precursor to avoid the detachment of copper stabilizer.

IX. Conclusion

We achieved the first successful fabrication in the world of a Rutherford cable with Cu stabilized Nb_3Al strands, producing a viable cable with acceptable Jc degradation. The cable test up to 11 Tesla external field with full transport current, and successful fabrication and excitation of a small model magnet SR04 proved that the Nb_3Al Rutherford cable could be excited to near its short sample data.

Although there are still much more improvements to be made in the Nb_3Al strand and Rutherford Cable, judging from our test results, the Nb_3Al Rutherford cable was shown to be viable for its application for high field accelerator magnets, possibly beyond 15 Tesla Magnets.

The well known advantage of the Nb_3Al strand over the Nb_3Sn strand is its stronger stress-strain characteristics. The Nb_3Al cable could be applied where the compressive force is beyond 150 MPa, and where Nb_3Sn cables will suffer. Secondly with Nb_3Al cable there is no strong degradation effect due to the Rutherford cabling operation, like the tin leakage in the Nb_3Sn cables. This point will be more important for strands with finer filament strands, below 50 μm size of subelements.

Because of its stronger strain-stress characteristics, Nb_3Al Rutherford cable could be used also for magnets made with React-Wind method.

With further improvements in the current density, Jc, reduction of the magnetization with use of Ta matrix, and reduction of its production cost, it could be used in many fields as well as in high field accelerator magnets. One example could be its application in the detector solenoid where the local magnetic field strength goes beyond 10 Tesla.

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