Quench Tests and FEM Analysis of Nb_3Al Rutherford Cables and Small Racetrack Magnets

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***Abstract*—In collaboration between NIMS and Fermilab, we have made copper stabilized Nb_3Al Rutherford cables, using Nb-matrixed and Ta-matrixed strands. First these cables were investigated at high current in low self field using a flux pump. Using these Rutherford cables, we built and tested small racetrack magnets. The magnet made with the Nb-matrixed strand showed the flux jump instability in low field. The small racetrack magnet wound with the Ta-matrixed Nb_3Al Rutherford cable was very stable at 4.5 K operation without any instability, as well as at 2.2 K operation. With the successful operation of the small racetrack magnet up to its short sample data, the feasibility of the Nb_3Al strand and its Rutherford cable for their application to high field magnets is established. The characteristics of Nb_3Al Rutherford cable is compared with that of the Nb_3Sn Rutherford cable and the advantages of Nb_3Al Rutherford cable are discussed.**

***Index Terms*—Low Field Instability, Nb_3Al Strands, Quench, Rutherford Cable, Small Racetrack Superconducting Magnet**

I. Introduction

At Fermilab, small racetrack magnets (SR) are used for quick testing of high current Rutherford cables made from newly developed superconducting strands [1]. The most recently constructed and tested Nb_3Al small racetrack magnet (SR07), is shown in Fig. 1. Two layer coil was wound from one piece of cable in the same direction in the common coil configuration. It has the gap of 2 mm to achieve the highest field between two layers. In the past we have made and tested 4 SR magnets using Nb_3Sn strands, one with the PIT strand, one with the MJR strand and two with RRP strands with two different subelement configurations.

Recently we have manufactured and tested Nb_3Al Rutherford cables at Fermilab, using three different Nb_3Al strands, which were manufactured at National Institute for Material Sciences (NIMS) in Japan, They were named with the starting letter F (meaning Fermilab) and with a series number, like F4 Nb_3Al Strand. Using these Nb_3Al Rutherford cables we have made three SR magnets SR04, SR05 and SR07. Two of them SR04 and SR07 magnets were tested at Fermilab. We decided not to test the SR05 magnet, because of limited availability of the test facility and due to its expected performance limitation because of not having enough twisting in F3 Nb_3Al strand. The F3 stand was made before the F4 strand similarly with Ta matrix, but could not be twisted due to its production schedule. The detailed test results of the SR04 magnet are reported in a previous paper [2], which describes its low field instability is due to Nb matrix and also due to not having enough twisting in the F1 strand.

In this paper we describe the characteristics of the Nb_3Al Rutherford cable made of F4 Ta matrixed strands and its magnet SR07. The 3 D quench behavior of the SR07 magnet was simulated using a commercial FEM program ANSYS [3] in three dimensions and is also presented in this paper.

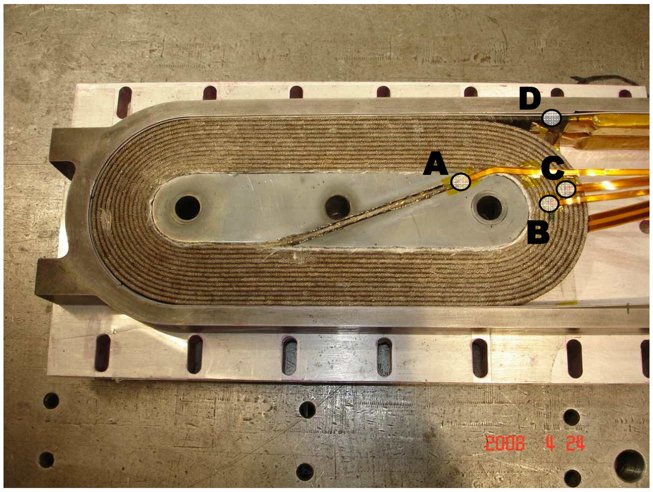

Fig. 1. The coil of the SR07 magnet is shown here after its heat treatment and just before epoxy impregnation. The central connecting cable is shown in the central iron pole just after rising from the bottom coil up to the top coil. The locations of the central voltage tap A and the intermediate voltage taps B and C, and the voltage tap at the splice D for the top coil are indicated.

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II. Construction of SR04 and SR07 Magnets

A. Nb_3Al strands and its Rutherford cables

The cross section of the newly developed Ta matrixed F4 Nb_3Al strand, which was used for the SR07 magnet, is shown

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in Fig 2. Its detailed characteristics are reported [4] and listed in the Table I, together with those of F1 Nb_3Al strand, which was used for the magnet SR04.

The cross sections of the rectangular F1 Rutherford cable with a low compaction factor and the rectangular F4 Rutherford cable with a high compaction factor are shown in Fig. 3 and Fig. 4 respectively. As the Nb_3Al core is much harder than the copper, the copper stabilizer is much more deformed compared to the core. Their Vickers hardness number of the Nb_3Al core is about 420 and that of the copper is 60. The strands at edges of the Rutherford cables showed a small void occasionally with the F1 cable, due to copper separation from the Nb_3Al core. This happened much less with the F4 cable, because the F4 strand was made with the improved electroplating technique [4].

Both F1 and F4 cables were tested with the flux pump method in its self field [5]. Their test results are shown also in the Table I. The F4 cable did not quench up to 25 kA.

The F1 cable was extensively tested in the external magnetic field at CERN's FRESCA facility at 4.3 K and 1.9 K at ramp rates from 100 to 1000 A/s. In general, the F1 cable was unstable and quenched in the low field region next to the joints with the NbTi power lead cable due to its low field instability. This is caused by its flux jump due to huge magnetization arising from Nb matrix [6].

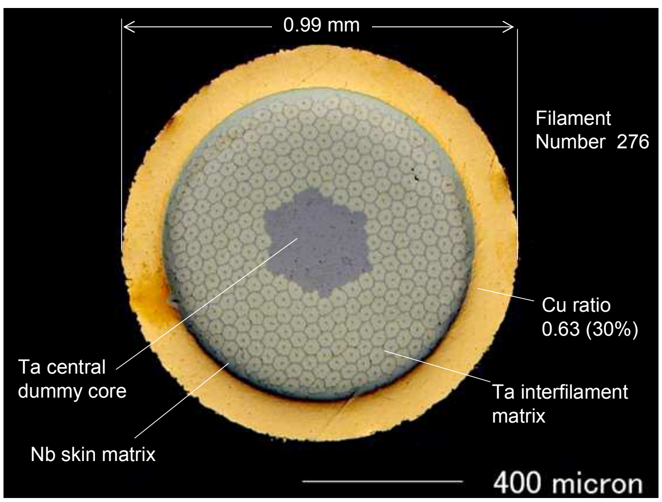

Fig. 2. The cross section of the Ta matrixed F4 Nb_3Al strand.

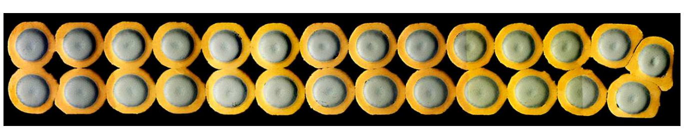

Fig. 3. The Cross-section of a rectangular Nb matrixed F1 Nb_3Al Rutherford cable with a low compaction factor 82.5 %. Dimensions: 14.2 mm x 2.0 mm.

Fig. 4. The Cross-section of a rectangular Ta matrixed F4 Nb_3Al Rutherford cable with a high compaction factor 86.5 %. Dimensions: 13.95 mm x 1.85 mm.

B. SR04 and SR07 Magnets

The parameters of the small racetrack magnets SR04 and SR07 are listed in the Table II. To wind the SR07 magnet a 14 m Rutherford cable was used. These Nb_3Al Rutherford cables are insulated with overlapping 0.15 mm thick ceramic tapes, because of its heat resistance. The wound coils were heat treated for 14 hours at 800 ºC. The physical distance between the opposing edge surfaces of the top and bottom cable conductors is minimized to 2 mm to enhance the gap field.

TABLE I
PARAMETERS OF F1 AND F4 NB_3AL STRANDS AND CABLES OF SR MAGNET

MAGNET	SR04	SR07
Nb_3Al Strand	F1	F4
Diameter(mm)	1.03	0.99
Diameter w/o copper (mm)	0.72	0.78
Area Reduction (%)	71.6	65.3
Cu Electroplating Velocity	2 m/h	10 m/h
Nb_3Al Filament Dia (μm)	50 (hexagonal)	35.8 (hexagonal)
No. of Filament	144	276
Matrix between Filaments	Nb	Ta
Most outside Matrix	Nb	Nb
Cu/non-Cu Ratio	1.0	0.61
Twist Pitch (mm)	362	45
Ic (4.2 K, 12T / 15T) (A)	582.9 / 351.5	645.9 / 376.5
Non-Cu Jc (A/mm^2) (4.2 K, 12T / 15T)	1,400 / 844	1,352 / 788
RRR of Cu	150 ~ 200	150 ~ 250
n-Value (4.2K, 12T / 15T)	40.3 / 35.5	40 / 34.3
Rutherford Cable	Rectangular	Rectangular
No. of Strands	27	28
Wide : high (mm x mm)	14.2 w, 2.0 h	13.95 w, 1.85 h
Compaction Factor (%)	82.5	86.5
Lay Angle (°)	15	15
Iq (4.3K, 10 T) (kA)	17.8	not tested
Iq (1.9K, 11 T) (kA)	20.2	not tested
Flux-pump Test (kA)	27.4 at 1.5 T	>25.0 No Quench

TABLE II PARAMETERS OF NB_3AL SMALL RACETRACK MAGNET

MAGNET	SR04	SR07
Cable	F1 with Nb matrix	F4 with Ta matrix
Maximum Current (kA)	21.76 at 3.95 K	25.2 at 2.1 K
Capable Max. Current (kA)		24.5/27 at 4.5/2.1K
Calculated Peak Field (T)	9.3	10.2
Capable Max. Field (T)		9.75 /10.75 at 4.5/2.1K
Aperture (mm)	2	2
No. of Coil Layers	2	2
No. of Turns / Coil	12	13
OD of Iron Yoke (mm)	215	215
Stored Energy @11T, kJ/m	19.1	19.1
Inductance @11T, mH/m	0.043	0.05
RRR	244 ± 20	120 ± 10
Resistance of Splice (nΩ) (+ / - leads)	0.38 / 0.38	0.2 / 0.3

C. Instability of F1 Nb_3Al Strand and Cable and Stability of F4 Nb_3Al Strand and Cable

With the first Nb_3Al strand F1, the Nb_3Al filaments are imbedded in the Nb matrix, which has the Tc of 9.26 K and the B_{c2} (4.2 K) of less than 0.5 T.

For the SR04 magnet wound with the F1 cable, we observed instability at low field region [2]. When the external field is raised from zero to ~ 0.5 T, shielding currents with a cosine shape distribution are generated on the outer surface of the strand including the Nb skin matrix area. At higher field from 1 to 1.5 T, the inter-filament coupling currents are generated in the Nb_3Al subelments. These coupling currents go through the locally still superconducting inner Nb matrix. These will generate an overall negative field inside the strand, reducing the effect of the external field. This effect will show up as an anomaly of magnetization, eventually causing a big flux jump when the outer field is further increased beyond 1.5 T. This is considered to be the cause of the instability of the F1 strand and cable [6]. Further detailed study is presented in another paper [7].

The SR07 magnet is made with Ta matrixed F4 strands. As the transition temperature of Ta is about 4.48 K, Ta is not superconducting at 4.5 K. F3 and F4 strands, both Ta matrixed strands do not show anomaly in their magnetization at 4.5 K, as is shown in Fig. 5(a) for the F3 strand measured at 4.2 K. Therefore at 4.5 K operation we did not observe any instability with the SR07 magnet as was the case with the SR04 magnet.

But at 1.9 K we observed a smooth anomaly of the magnetization curve with a similarly Ta matrixed F3 strand as is shown in Fig. 5(b) [8]. But at 2.2 K the SR07 magnet did not show any low field instability because the B_{c2} of Ta is less than 0.01 Tesla [7].

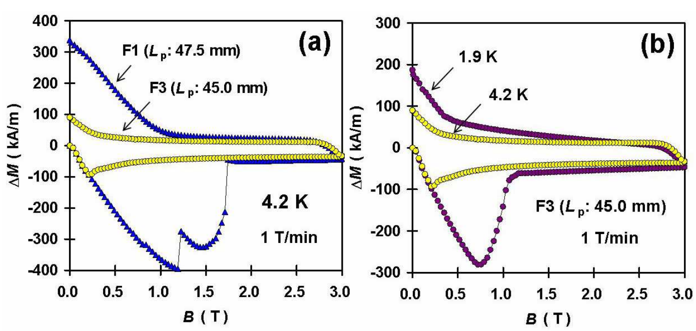

Fig. 5. 5(a) shows magnetization curves of Nb matrixed F1 and Ta matrixed F3 strands at 4.2 K. 5(b) shows those of Ta matrixed F3 strands at 1.9 K and 4.2 K. F3 an F4 strands are similarly structured and both have Ta matrix.

III. TEST OF SR07 MAGNET

A. Quench History

The detailed test data of the SR07 magnet are reported in an internal Fermilab technical note [9]. For the test of the low inductance SR07 magnet, the ripple of the power supply was kept low to peak to peak of 30 A. The other problem with the power supply was at the mechanical and electrical joint at the bottom of the positive 30 kA copper power lead. As it was not perfectly assembled, it generated heat and caused rapid falling of the liquid He level. At the beginning of the quench test of this magnet we had several trippings due to the power leads at the slow ramp rate testing.

B. Ramp Rate Dependence and Temperature Dependence

As this magnet did not show any training, we went through the ramp rate dependence test at 4.5 K and 2.2 K. Its test data are shown in Fig. 6.

In the region below 100 A/s, the magnet SR07 showed a gradual decrease in quench current toward the zero ramp rate point, due to heating of the copper lead junction which eventually induced some voltage in the joining NbTi power leads, as described above.

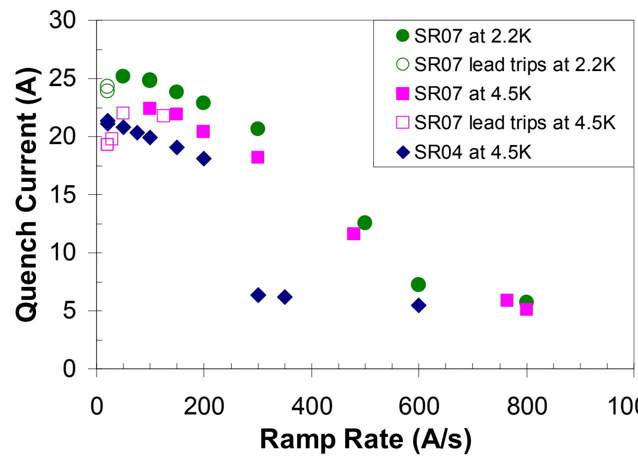

Fig. 6. Ramp rate dependence of the SR07 magnet at 4.5 K and 2.2 K operation, shown together with that of the SR04 magnet at 4.5 K.

The ramp rate dependence shows a smooth curve up to 500 A/s at 4.5K, but at 2.2 K it show an abrupt decrease at 600 A/s. The ramp rate dependence curve at 2.2 K of the magnet SR07 is lifted up by about 2.5 kA relative to that of 4.5 K operation below the 300 A/s range.

The ramp rate dependence of the SR04 magnet is roughly 2.5 kA down relative to that of the SR07 magnet at 4.5 K and below 200 A/s range, showing an abrupt decrease at 300 A/s.

The temperature dependence of the quench current of the SR07 magnet is shown in Fig. 7. It shows the quench current decreases by 0.7 to 1.3 kA/K in the region from 2.2 to 4.5 K.

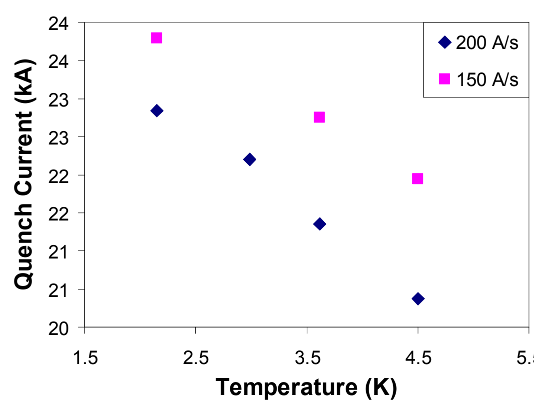

Fig. 7. Temperature dependence of the quench current of the SR07 magnet.

C. Quench Location

All of the quenches at 2.2 K operation occurred in the top coil. At 4.5 K operation the entire high current quenches above 15 kA occurred in the top coil except one. But all of the quenches below 15 kA occurred in the bottom coil.

The typical quench scan data is shown in Fig. 8. It corresponds to the voltage tap data of a quench at 150A/s at 4.5 K. It shows the quench starts from the region between the center tap A to its 4th turn tap B, the segment A-B. Then it propagates to the next central 4 turns, and to the outer 5 turn region. If we calculate a simple quench propagation velocity along the cable length, it may show 460 m/s. Or if we calculate transverse propagation, it will be in the order of 40 mm/s.

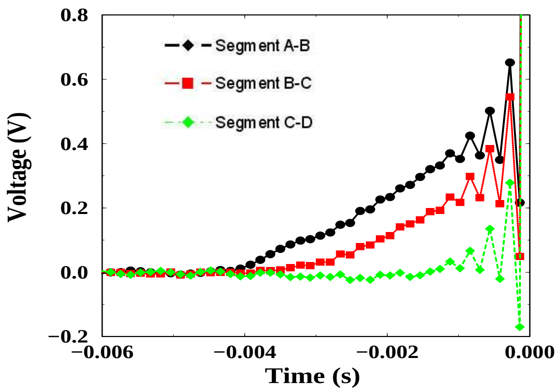

Fig. 8. Quench scan data of the SR07 at 150 A/s at 4.5 K operation.

D. *Energy Loss measurements*

The energy loss per cycle of the SR07 magnet was measured at 4.5 K, with the current cycled from 500 to 6,500 A at ramp rates from 200 to 600 A/s. It is shown in Fig. 9. From this data the hysteresis loss is estimated to be about 65 Joule/cycle.

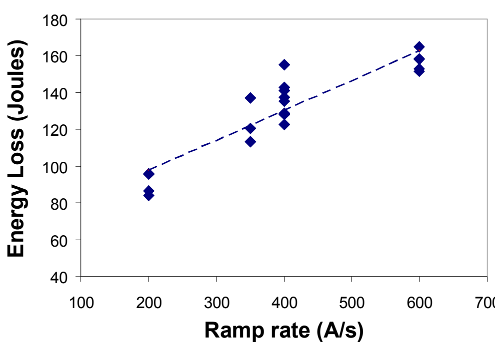

Fig. 9. Energy loss measurement of the SR07 at 4.5 K.

IV. Maximum Quench current of SR07 magnet

By extrapolating the quench data points at 2.2 K and 4.5 K in Fig. 6 down to the zero ramp rate point, we can deduce the maximum quench current values, judging from the previous test of the SR03 magnet [1]. If we did not have the Cu power lead problem, we could expect the maximum quench currents would be 24.5 kA at 4.5 K and 27 kA at 2.2 K.

The estimated maximum quench current data of the SR07 magnet are shown in Fig. 10 on its load line. They are compared with the short sample data of the F4 Rutherford cable, which were calculated from the witness samples of round and extracted F4 strands, measured at 4.2 K.

From Fig. 10, the SR07 magnet is estimated having attained 100 % short sample data, if there were no the power supply lead problem. Also this data shows the degradation of the F4 strands due to cabling is small, about 2.4 % at 12 T.

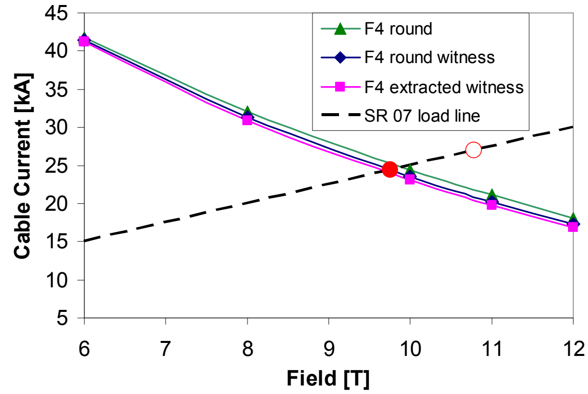

Fig. 10. The load line for the SR07 magnet and its short sample cable data measured at 4.2 K are shown. The estimated highest quench value 24.5 kA at 4.5 K corresponds to 9.7 Tesla, and is marked with a filled circle. At 2.2 K the estimated 27 kA quench point, is marked with an open circle, and corresponds to 10.7 Tesla.

V. Quench simulation of SR07 Magnet

The 3-D magnetic field of the SR07 magnet is calculated with ANSYS, assuming the gap between the opposing coils is 2 mm. Its field distributions in the median plane are shown in the previous paper [2]. In the cross section of the Rutherford cable only the inner edges are subjected to the highest field, so it is expected that the quench starts at these localized inner edges. As the cable is subject to the very non-uniform field distribution across the width of the cable, we should expect current sharing between the neighboring strands in the cable.

From these observations, we simulated its three dimensional quench propagation. The quench propagation at 0.6 ms is shown in Fig. 11. Its on-line movie is displayed at its website [10].

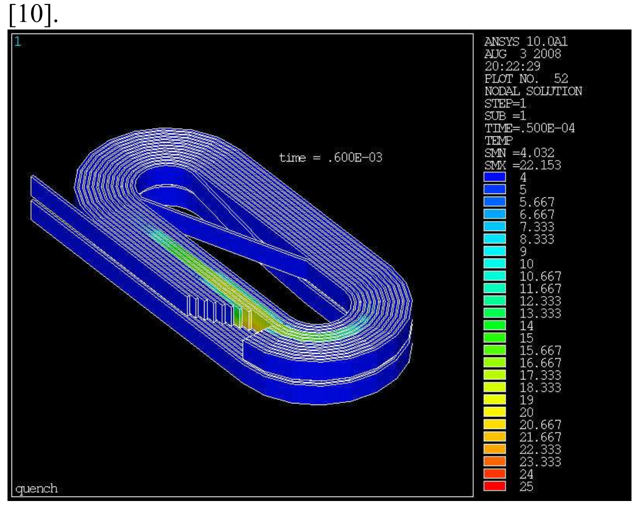

Fig. 11. 3-dimensional quench simulation of the SR07 magnet. The top coil is cut out to show the quench starting part in the median plane. This is a part of a movie file at 0.6 ms after the start of the quench.

Basically ANSYS is used to provide solutions for the simple thermal conduction problem. The rest of quench sequence including calculation of heat generation and normal transition is handled with an ANSYS's script program. Consequent analysis gives temperature distribution view and stored in a movie file. It is noted that the quench velocity is very fast because of the turn-to-turn propagation.

VI. Comparison of Data of SR magnets

In Table III the maximum current and field values are shown for four tested SR magnets. The magnet SR03 and SR06 were wound with Restacked Rod Process (RRP) Nb_3Sn strands and the magnet SR04 and SR07 are wound with Nb_3Al strands. The maximum quench current values of SR03 and SR07 magnets are extrapolated data, assuming the power leads were in good condition. All SR magnets are made of 13 turn/coil, except SR06, which is made of 12 turn/coil.

The test results of the SR07 Nb_3Al magnet are reasonable compared to the SR03 Nb_3Sn magnet data. There is 10 % difference between their maximum current values. The copper ratio of F4 Nb_3Al strand was intentionally reduced to make its Ic value bigger.

Another remarkable thing of the SR07 magnet is that it did not have any training, while other Nb_3Sn magnets had extensive training. But this may be partly due to the improvements in the construction technique. Or due to the extra hardness of the Nb_3Al strands, any movement of conductor or cracking of the epoxy might be prevented.

SR03 and SR06 magnets are made 2 years apart with RRP strands, which were also made 2 years apart using similar specifications but with different configurations, expecting similar results. But the magnet SR06 turned out unstable at 2.2 K operation as is shown in the Table III. Sometimes the Nb_3Sn strands are not consistent in their quality, which may be due to cable damage during Rutherford cabling process or during magnet production process.

TABLE III Comparison data of Tested SR Magnets

SR Magnet / Strand	Imax (~4.5K) //Bam	Imax (~2.1K) //Bam
SR03 / Nb_3Sn, RRP	27.5 kA, 4.5 K// 10.9 T	30 kA, 2.2 K// 11.9T
SR04 / Nb_3Al, F1	21.8 kA, 4.0 K// 8.7 T	Low field instability
SR06 / Nb_3Sn, RRP	28.6 kA, 4.5 K// 10.3 T	26.6 kA, 2.2K// 9.7 T
SR07 / Nb_3Al, F4	24.5 kA, 4.5 K// 9.7 T	27 kA, 2.2K// 10.7T

VII. Discussion

As can be seen from Table III, the comparison table with other Nb_3Sn SR magnets tested, the SR07 magnet seems comparable with Nb_3Sn SR magnets.

The Ta matrixed SR07 magnet is the first stable high field dipole magnet built using the fully copper stabilized Nb_3Al strand. It did not have any training characteristics, and achieved 100 percent short sample data.

It is also completely free from low field instability both at 4.5 and 2.2 K operation, which we experienced with the Nb matrixed SR04 magnet.

VIII. Conclusion

With the successful and stable operation of the small racetrack magnet SR07, the feasibility of the Nb_3Al strands and its Rutherford cables for their application for the high field magnet is now established. We now know Nb_3Al Rutherford cables can be made without any problem,

There are still more to be done in its development. Its current density should be increased if possible, and its cost should be decreased. But we can expect its application to practical magnets will be developed in the near future.

Nb_3Al strands and its Rutherford cables have many advantages over the Nb_3Sn strand and cables. They have higher strain tolerance, possibility of smaller filament diameters, and much less time needed for heat treatment and no tin leakage problem, which is a persistent problem with cabled Nb_3Sn strands.

There will be some special application area for the Nb_3Al strands and cables. They could be especially developed for applications with much finer filament size in higher field and higher stressed application beyond Nb_3Sn usage.

IX. Acknowledgement

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