Quench Tests of Nb_3Al Small Racetrack Magnets

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***Abstract*—Two Cu stabilized Nb_3Al strands, F1 (Nb matrixed) and F3 (Ta matrixed), have been made at NIMS and their Rutherford cables were made at Fermilab in collaboration with NIMS. A Small Race-track magnet using F1 Rutherford cable, the first Nb_3Al dipole magnet in the world, was constructed and tested to full current at Fermilab. This magnet was tested extensively to full short sample data and its quench characteristics were studied and reported. The 3-D magnetic field calculation was done with ANSYS to find the peak field. The quench characteristics of the magnet are explained with the characteristics of the Nb_3Al strand and Rutherford cable. The other Small Race-track magnet using Ta matrixed F3 strand was constructed and will be tested in the near future. The advantages and disadvantages of these Nb_3Al cables are discussed.**

***Index Terms*—Cable Test, Quench, Nb_3Al, Rutherford Cable, Small Superconducting Magnet**

I. Introduction

The small race track magnet was originally developed at LBNL for quick testing of Nb_3Sn Rutherford cables [1]. Its two racetrack coils are wound in opposite direction as for the common coil configuration, as shown in Figure 1. In order to test the Rutherford cable at high field the distance between two coils is made extremely small. At Fermilab, we made small racetrack coil magnets (SR), with slight modifications to the LBNL design and are now using them as a standard quick method for testing the high current Rutherford cables [2].

The SR04 and SR05 magnets are the first high field dipole magnets built using the fully copper stabilized Nb_3Al strands manufactured by the National Institute for Materials Science (NIMS) in Japan. Making Rutherford cables with Nb_3Al strands and the construction and testing of SR magnets were done at Fermilab in collaboration with NIMS. The magnet construction and instrumentation are identical to the previous SR magnets in the series [2]. The SR04 magnet was fabricated in June 2006 using the F1 Nb_3Al strand and tested in September 2006. The SR05 was made in August 2007 using F3 Nb_3Al strand and will be tested in the fall of 2007.

The magnetic field distribution of the magnet was calculated with ANSYS in three dimensions and is presented here.

The test results of the SR-04 magnet are presented with respect to its training, ramp rate behavior and AC loss measurement.

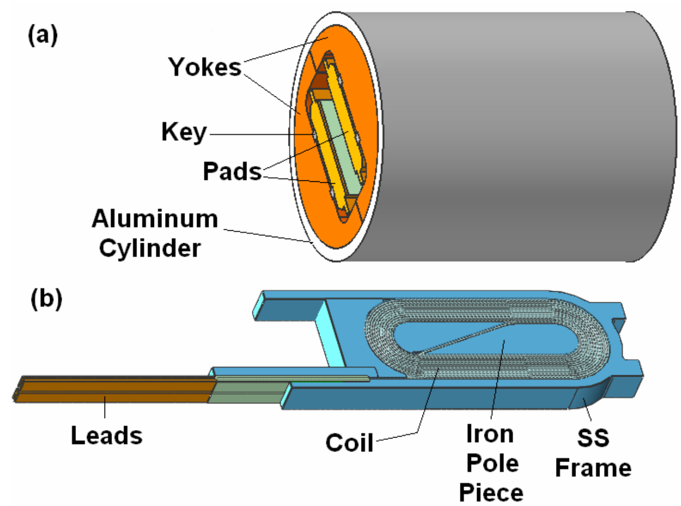

Fig. 1. Geometry of SR magnets.
(a) shows the assembly of an aluminum cylinder, yokes, keys and two steel plate pads. (b) shows the two-layer coils, connected in the opposite direction, a center iron pole, and a stainless frame. The peak field is generated in the narrow 2 mm gap between the opposing small racetrack coils.

II. Construction of SR04 and SR05 Magnets

A. Nb_3Al strands and its Rutherford cables

The detailed characteristics of the copper stabilized strands F1 and F3 are described separately in other papers [3] and [4] respectively. Their major parameters are listed in Table I.

The cross sections of the rectangular F1 Rutherford cable with low compaction factor and the key-stoned F3 Rutherford cable with high compaction factor are shown in Fig. 2 and Fig.3 respectively. The parameters of F1 Rutherford cables are reported in a previous paper [5] and also listed in the Table I, together with F3 cables. As the Nb_3Al core is much harder than the copper, the copper is much more deformed. Their Vicker's hardness numbers are about 420 and 60, respectively. The strands at the edges of the Rutherford cables show a small void occasionally, due to copper separation from the Nb_3Al core. This happened much less with F3 cables, because the F3 strand was made with improved electroplating

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techniques.

Both F1 and F3 cables were tested with the flux pump method in its self field [5], [7]. Their test results are shown also in the Table I.

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, as is shown in Fig.9 [5]. In general, the cable was unstable and quenched at the splice due to its low field instability, caused by its flux jump due to huge magnetization as mentioned later in Section *C*.

TABLE I
PARAMETERS OF Nb_3Al STRANDS AND CABLES OF SR MAGNETS

MAGNET	SR04	SR05
Nb3Al Strand	F1	F3
Diameter(mm)	1.03	1.0
Nb3Al Filament Dia (μm)	50 (hexagonal)	38
No. of Filament	144	222
Matrix between Filaments	Nb	Ta
Cu/non-Cu Ratio	1.0	1.0
Twist Pitch (mm)	362	>1000
Ic (4.2 K, 12T/ 15T) (A)	582.9 / 351.5	581.3 / 343
Non-Cu Jc (A/mm^2)	1400 / 844	1481 / 874
RRR of Cu	150 ~ 200	80 ~ 170
Rutherford Cable	Rectangular	Key-Stoned
No. of Strands	27	27
Wide : high (mm x mm)	14.2 wide, 2.0 high	14.2 w, 1.78 ave.
Narrow : thick Edge (mm)		1.68 : 1.88
Compaction Factor (%)	82.5	87.2
Key-stoned Angle (°)	0	0.7
Lay Angle (°)	15	15
Iq (4.3K, 10 T) (kA)	17.8	-----
Iq (1.9K, 11 T) (kA)	20.2	-----
Flux-pump Test (kA)	27.4 at 1.5T	>24

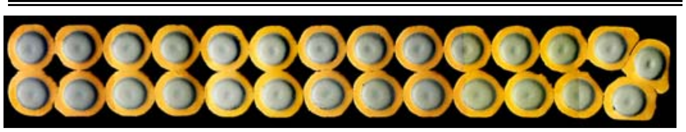

Fig. 2. Cross-section of a rectangular F1 Nb_3Al Rutherford cable with a low compaction factor 82.5 %. 14.2 mm x 2.0 mm.

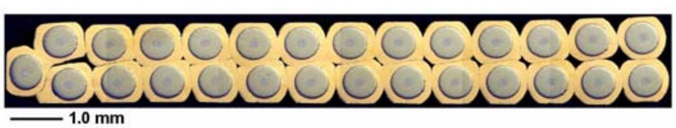

Fig. 3. Cross-section of a key-stoned F3 Nb_3Al Rutherford cable with a high compaction factor 87.2 %. 14.2 mm x 1.78 mm average.

TABLE II
PARAMETERS OF Nb_3Al SMALL RACETRACK MAGNETS

MAGNET	SR04	SR05
Maximum Current (kA)	21.76 at K	----
Calculated Peak Field (T)	9.3	----
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	----
Resistance of Splice (nΩ)	0.38 / 0.38	----

B. SR04 and SR05 Magnets

The parameters of the small racetrack magnets SR04 and SR05 are listed in the Table II. Their coils are made of two layers, which are connected in the opposite direction in the common coil manner. The total cable length of the SR05 magnet is 14 m. These Nb_3Al Rutherford cables are insulated with overlapping 6 mil thick ceramic tapes, because of its heat resistance. The wound coils are heat treated in the following schedule: 20 to 500 ºC in 9.5 hours, 5 hours at 500 ºC, 6 hours to go to 800 ºC, 14 hours at 800 ºC, and decay to room temperature. The physical gap between the opposing cable conductors is 2 mm.

C. Instability of F1 Nb_3Al Strand and Cable and F3 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 9.25 K and the B_{c2} (4.2 K) of ~0.6 T.

During tests of the F1 strand [3], F1 cable [5] as well as a magnet wound with F1 cable, when the external field is raised from zero to ~0.5 T, the shielding current is generated inside the filaments, but also the inter-filament coupling currents are generated through the still superconducting Nb matrix. The aggregate inter-filament currents will generate an overall negative field inside the strand, which reduce the effect of the external field. This effect will show up as an anomaly of magnetization and end up as a big flux jump. This is considered the cause of the instability of this F1 strand and cable [6].

During the production of the F3 strand, we could not twist the strand, due to the planned production process. This will be corrected in the future production.

III. MAGNETIC FIELD CALCULATION OF THE SR04 MAGNET

The three dimensional magnet structure is simulated with ANSYS program. In this analysis the 0.5 mm thick insulation is assumed to cover the conductor of the Rutherford cables. Also a 1 mm ground cover insulation layer between the two coils is incorporated into the analysis. Therefore the magnetic gap between the two coils is assumed to be 2 mm.

The 3-D magnetic field was calculated also with ANSYS. For simplicity the two coils are simulated as two independent current loops with opposite current direction, neglecting the central connecting jumper cable. Results are shown in Fig. 4 and Fig. 5. In Fig 4, the magnetic flux density at the top edge surface of the conductors in the median plane is shown, indicating its maximum field is 9.3 Tesla. The directions of the magnetic field on the surface of the coil are also indicated with arrows. The center iron pole field varies from 3 to 6 Tesla. In Fig. 5, the magnetic flux density is shown in the mid-plane perpendicular to the axis of the magnet. The directions of the magnetic field in the gaps are indicated with arrow signs.

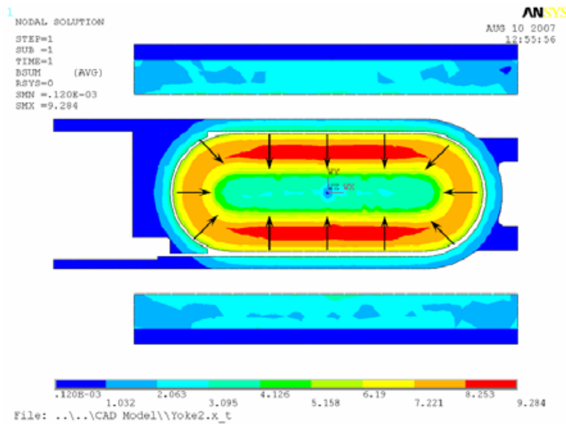

Fig. 4. The magnetic flux density distribution on the inner surface of the coil conductor. Its maximum field is 9.3 Tesla at the straight sections.

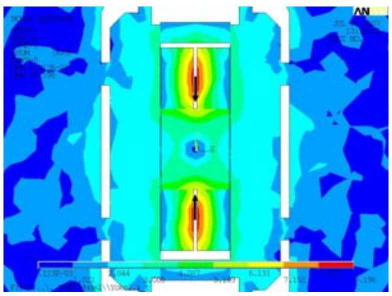

Fig. 5. The magnetic flux density distribution in the middle cut section of the whole magnet. It shows the inner most surface of the conductor has the highest flux density of 9.3 Tesla.

From these pictures the peak fields are at the inner edges of the mid-turn cables of the coil, around 6 turns in the straight section. In the cross section of the Rutherford cable only the inner edge is subjected to the highest field. It can be expected that these localized inner edge points are the starting points of the quench. As the voltage taps were only at the center of the two coils and at both splices with the SR04 magnet, we could not measure the quench velocity. With the SR05 magnet, we installed four more voltage taps, two on each coil.

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.

IV. Test of SR04 Magnet

A. Quench History

The detailed test data are reported in a Technical Report [8]. Because of the low inductance of the magnet about 30 μH, at first we had problems with power supply regulation and analog quench detection thresholds. This resulted in a number of data points with low current trips. At the beginning, the current ripple was 300 A p-p, which was later reduced by a factor of 6 with a better power supply regulator.

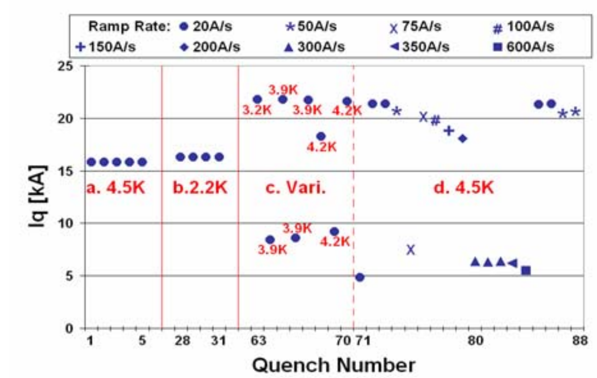

Figure 6. Quench history a) 4.5K 20A/s training with big ripples in current. b) 2.2K 20A/s training with big ripples, c) temperature dependence with reduced ripples, d) 4.5K ramp rate dependence with reduced ripples.

The quench data history is shown in Fig. 6, where the data points due to obvious power supply tripping are eliminated. Up to the quench 63, we suffered from massive tripping. As can be seen from this figure, we still suffered from the power supply regulation up to the data point 72. Obviously this data is not a training curve. The data points before 31 are low because of big ripple current, causing ac loss in conductor.

After reducing the ripple current, the highest quench current of SR04, 21,764 A, was reached at 3.95 K. Its peak field is 9.3 Tesla. For reference the SR03 magnet wound with RRP strands from OST was excited up to 28,048 A at 2.2 K and 50 A/s without quenching.

B. Quench Location

The small racetrack magnets have very few voltage taps for quench characterization. With many quenches, especially with the quench current over 19 kA, a voltage development is seen in both coils. For some of the low current quenches, development was so slow (more than one second) that the origin is not observed in the data logger quench window.

C. Ramp Rate Dependence

Ramp rate dependence is summarized in Fig. 7 for the low amplitude ripple case at 4.45 and 2.16 K. The performance drops dramatically above 200 A/s at 4.45 K. At 2.16K the quench current steadily drops up to 200 A/s, and recovers at 300 A/s. It eventually decreases above 400/s. This is not well understood. It might be caused by the instability at low field, the lower heat capacity of the material and the heating by the ac loss due to the remaining ripple current.

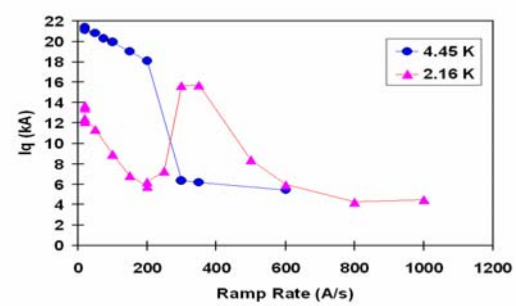

Figure 7. Current ramp rate dependence at 2.2 K and 4.5 K.

D. Temperature Dependence

The temperature dependence is shown in Figure 8. The data points around 4 K are fluctuating due to the instability of the F3 strand. With more improvements in power supply, the quench current might be solidly around 22 kA. At 2.2 K, the quench current at 350 A/s, is higher than data at 20 A/s, as is shown in the previous section C. Ramp Rate Dependence.

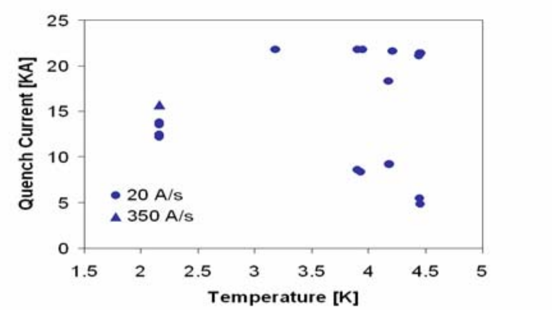

Figure 8. Temperature dependence of quench current at 20 A/s. The triangle point shows 350 A/s peak quench current at 2.2K. All others at 20 A/s.

E. Energy Loss measurements

The energy loss per cycle was measured with small current ripple. The current was cycled from 500 to 6500 A. From this data the hysteresis loss is estimated 37 ± 7 Joules.

V. SR04 Magnet Quench Data and Cable Quench Data

With the SR04 magnet wound with the F1 Nb_3Al Rutherford cable, the maximum current achieved was 21.76 kA at 3.95 K at 20A/s corresponding to 9.3 Tesla peak field in unsteady mode. The maximum quench data of the SR04 are shown in the Fig. 9 together with the test data of the F1 Rutherford cable, which were measured at CERN's FRESCA in the external field [5]. The load line of the magnet and the short sample data of the F1 Rutherford cable are also shown in this figure, indicating the quench data is at about 98 % of the short sample data.

VI. Conclusion

With the successful operation of the small racetrack magnet SR04 up to its short sample data, the feasibility of the Nb_3Al strands and its Rutherford cables for their application for high field magnet is now established.

There are still more to be done in its development, for its stability, current density and cost. But we expect that its applicability for practical magnets will be developed in near future.

Because it has many advantages over the Nb_3Sn strand and cables, like higher strain tolerance, no tin leakage problem, possibility to smaller filament diameter, and much less time needed for heat treatment, there will be some special usage area for the Nb_3Al cables. It could be especially developed for applications with much finer filament size in higher field and higher stressed application beyond Nb_3Sn usage.

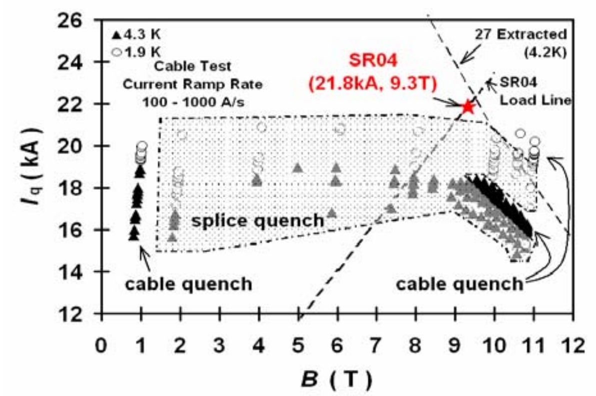

Fig. 9. The load line for SR04 magnet and its highest quench value 21.8 kA at 9.3 Tesla at 3.95 K are shown. Quench values of the F1 Nb_3Al Rutherford cable tested at CERN at 1.9 K and 4.3 K are shown together.

VII. Acknowledgement

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