Feasibility Study for 15-Tesla Magnet using Rapid-Heating Quenching and Transformation Nb$_3$Al Strand

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Abstract. A new practically long copper stabilized Rapid-Heating Quenching and Transformation (RHQT) Nb$_3$Al strand is presented, which is being developed and manufactured at the National Institute of Material Science (NIMS) in Japan. It has achieved a non-copper $J_c$ of 1000 A/mm$^2$ at 15 T at 4.2K, with a copper over non-copper ratio of 1.04, and a filament size about 50 μm. Using this strand the feasibility study of a 15 T dipole magnet is presented. For this study a Rutherford cable with 28 Nb$_3$Al strands of 1 mm diameter will be fabricated early in 2006. A block-type magnet is designed using ROXIE, and the stress and strain in the coil is estimated and studied with the characteristics of the Nb$_3$Al strand. The advantages and disadvantages of the Nb$_3$Al cable are compared with the prevailing Nb$_3$Sn cable from the point of view of stress-strain, and possible effects on $J_c$ due to cabling is presented. The Nb$_3$Al coil of the magnet, which will be made by wind and react method, has to be heat treated at 800 degree C for 10 hours. As preparation for the 15 T magnet design, a series of tests on strands and Rutherford cables is presented.

Keywords: Nb$_3$Al, RHQT, Rutherford cable, High Field Superconducting Accelerator Magnet

1. Introduction

The LHC magnets are now being produced with NbTi strands as 9 T dipole magnets. In the last decade, many institutions have been working to develop 10 to 15 T dipole magnets utilizing Nb$_3$Sn strands for higher energy accelerator magnets [1, 2]. Nb$_3$Al strand were known to have higher compressive stress and higher axial strain tolerance than Nb$_3$Sn, and it was considered for accelerator magnets [3]. But it has been difficult to make a long stabilized Nb$_3$Al strand. Recently National Institute of Material Sciences in Japan succeeded to produce several hundred meter long stabilized Nb$_3$Al strands [4,5]. The detailed characteristics and production process of the recent copper stabilized RHQT Nb$_3$Al strand is reported in other paper [5]. As we are preparing now to make a Rutherford cable with the newly developed Nb$_3$Al strand, we enumerated the tests to be done with the strand, cables and a small scale magnet. We also presented a preliminary design of a 15 T magnet.

2. RHQT Nb$_3$Al Strand

The Rapid-Heating Quenching and Transformation (RHQT) Nb$_3$Al strand goes through several production processes.

2.1. Precursory Nb$_3$Al Strand

The present Nb$_3$Al strand is made by ‘Jelly Roll’ (JR) method. The alternate foils of Nb and Al (overall composition: Nb-25at%Al) are wrapped around a Nb rod, and on top of it another Nb foil is wrapped. The resulting composite is cold worked into a hexagonal wire as a monofilament. 132 monofilaments are stacked around the central Nb core and placed into a Nb can making a billet. This assembly is hydrostatically drawn and made into a thin multifilamentary wire.

2.2. RHQ, Rapid-Heating and Quenching

The JR processed Nb/Al multifilamentary wire, several hundred meters in length, is reel-to-reel Ohmic-heated rapidly to a very high temperature (~1900°C), quenched into a molten Gallium bath at ~50°C. Jelly Rolled Nb$_3$Al precursory conductors is made by exploiting the transformation from supersaturated bcc-solid-solution
(Nb(Al)ss). The resultant composite only includes the bcc Nb(Al)ss phase, and the ductility of the whole composite is ensured to make coils and cables, like a Rutherford cable.

### 2.3. Addition of Copper Stabilizer

The surface of the precursor strand is Cu ion planted in vacuum, and electroplated with Cu to add the thick copper stabilizer. Then it goes through sizing process [4,5]. At this stage the strand is very ductile at room temperature. The cross section of the 1 mm diameter strand is shown in figure 1, together with magnified picture showing the filament structure. The average filament size is 50 μm.

![Figure 1. The cross section of 1 mm diameter Nb3Al strand and its magnified picture of filament structure.](image)

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![Figure 2. Short sample data of 1mm RHQT Nb3Al strand measured at 4.2K.](image)

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### 2.4. Transformation by Final Heat Treatment

The strand is transformed into A15 phase by heating at 800°C for only 10 h. It enables to complete the reaction in a short time and suppresses the grain growth of A15 Nb3Al. The A15 RHQT Nb3Al strand transformed from Nb(Al)ss has a high stoichiometry, and it will have high critical current densities $J_c$. The short sample data at 4.2 K is shown in figure 2. The non-copper $J_c$ of 1000 A/mm² at 15 T at 4.2 K is achieved, and its $I_c$ current is 400 A. The Nb matrix/Nb3Al ratio is 0.6 and Cu/non-Cu ratio is 1.04. The detailed description of the strand production will be presented in MT-19 [5]. The Nb3Al strand need to be heat treated only in 10 hours at 800 K, and the regular short sample test is done with fast heating and cooling. But as the coil assembly cannot be brought up to 800 K in a short time, we have to heat up and down the coil assembly gradually. We have to test the strands in the similar gradual heat treatment modes to check the $J_c$ value for a possible change due to slow heat treatment.

### 3. Strain and Stress of Nb3Al Strand

The most advantageous point of the Nb3Al over Nb3Sn is its strength in respect to the stress and strain. The experimental data on the degradation of $J_c$ value versus axial strain and transverse compressive stress of the
RHQT Nb$_3$Al has been reported [6-9]. The degradation of the critical current $J_c$ at 12 T at 4.2 K of RHQT Nb$_3$Al strand with the intrinsic strain is shown in figure 3 together with the value for a typical Nb$_3$Sn strand. The shape of the degradation is the same for all different Nb$_3$Al strands, but the actual zero strain point is shifted due to the shrinkage of the copper stabilizer. In an example strand with a Cu/non-copper ratio of 0.39, the shift is at -0.26 %. It depends on the amount of the copper stabilizer. In the positive direction, pulling, the total strain of 0.3 % is acceptable and we can expect 4% increase in $J_c$. At 15 T, the intrinsic strain value in the figure will be reduced down to 70 %. For the compressive stress, a Nb$_3$Al (non RHQT) strand shows $J_c$ decreases by 10 % at 520 MPa, 9 T and 4.2 K, while a Nb$_3$Sn strand experiences same decrease in $J_c$ at 90 MPa [6]. We have to check this strain and stress problem at 15 T with our epoxy impregnated cable.

4. Extracted Strand Tests
After making a Rutherford cable, we will extract strands and heat treat them. We will do the short sample test on the extracted strands together with the original round strands, and we will investigate the degradation effect due to cabling if any. Compared with Nb$_3$Sn strands, we should expect less degradation in $J_c$ due to contamination and filament damage from cabling operation. The regular magnetization measurement will be done to observe the amount of flux jumps, which may cause some instability of the cable at low field. The bending strain test of strands will be done by testing reacted coils with small radius using bobbins with a smaller or a larger radius. Its test with Modified Jelly Roll Nb$_3$Sn strands is reported in a previous paper [10].

5. Rutherford Cabling of Nb$_3$Al Strands and its Test Methods
It is planned to make a 28 strand Rutherford cable with 1 mm Nb$_3$Al strands at Fermilab early in 2006. With 1 km of strand, we should be able to make about 30 meter long cable. A short cable itself will be tested with the flux pump method with full current at its self field [11]. We want to see the stability of the strand at low field with maximum current. We also want to test the sensitivity of the cable to transverse pressure under 15 T, as explained in the paper [12]. It is also planned to do the cable test with high transport current in the external high field magnet up to 10 T [13].

With a 20 meter cable, we will make a small racetrack coil magnet as a cable test based on Wind and React method. Its structure and its test results with the PIT Nb$_3$Sn cable is described in the other paper [14]. We will test the magnet up to its full current. With 25 kA current in the cable, the peak field in the racetrack coil will be 10 Tesla locally at the edge. This magnet has two layer small racetrack coils which are connected in the opposite direction and stacked tight together with 2.5 mm spacing between opposing conductors of two layers.

6. Design Study of 15 Tesla Block Type Magnet
The cosine theta 15 T magnet designs, mostly using Nb$_3$Sn strands are reported at MT-19 [15], and here we present briefly the 15 T block type magnet design made with Nb$_3$Al strands. The cross section of the 15 T magnet is shown in figure 4. The central bore size is 43.5 mm, but the horizontal opening of the first blocks is set to 50 mm, to accommodate a beam pipe and structural wall there. The maximum central field is 14.88 T at 4.5 K with the quench current of 10.23 kA, with a maximum field of 16.4 Tesla in the conductor. The field distribution inside the coil blocks is shown in figure 5. This design was done with Xroxie, using three blocks of 28 strand Nb$_3$Al cables with $J_c$ of 1,000 A/mm$^2$ at 12 T at 4.5 K. The averaged midplane stress of all block coils due to only Lorentze force is 85.4 MPa and the averaged horizontal stress at the outer surface of the blocks is 67 MPa respectively at 4.5 K operation, which is well within the safe operation region of Nb$_3$Al cable. At the maximum current, the total horizontal force is 300 ton/m/quadrant, and the compression at the midplane is 590 ton/m/quadrant. The central bore field can reach at 15.5 T with 10.72 kA at 1.9 K operation.
With this simple design of the iron yoke, the field distribution at low excitation is quite acceptable, but the effect of the saturation of the yoke is quite high at high field. We need a modification of yoke design with holes in the yoke.

7. Conclusions
In the mid-range of 15 Tesla for the accelerator magnet application, the Jc value of Nb3Al strand has been tremendously improved due to the invention of RHQT method. With the successful attachment of the copper stabilizer to Nb3Al, we think the Nb3Al strand can now be applied for the development of magnets in this field range. We think we can expect still more improvements in Jc and Ic values, and in strand manufacturing process. The major thing we hope for is to cut the production cost for a large scale production.

For a successful application and operation of Rutherford cables, there are a series of tests to be done as enumerated in this paper, which we hope we can carry out in one year. As an application to the 15 T magnets, we showed an example of a block type 15 T magnet, which can be designed and constructed with the present RHQT Nb3Al strand. Although we still have to work out many details, including the end design, we think we can design, build and test 15 T dipole magnets successfully using Nb3Al strands.

References
[1] Sabbi G, Bartlett SE, Caspi S, Dietderich DR, Ferracin P, Gourlay SA, Hafalia AR, Hannaford CR, Lietzke AF, Mattafirri S, McInturff AD and Scanlan R 2005 Design of HD2: a 15 Tesla Nb3Sn dipole with a 35 mm bore IEEE Trans. on Appl. Supercon. 15 pp 1128-1131
[2] Devred A et al. 2005 Status of the next European dipole (NED) activity of the collaborated accelerator research in Europe (CARE) project IEEE Trans. on Appl. Supercon. 15 pp 1106-1112
[3] Kobayashi T, Tsuchiya K, Shintomi T, Terashima A, Banno N, Nimori S, Takeuchi T, Tagawa K, and Iwaki G 2004 Development of Nb3Al superconducting wire for accelerator magnets IEEE Trans. Appl. Supercond. 14 pp1016-19
[4] Kikuchi A, Sakurai Y, Tagawa K, Takeuchi T, Kitaguchi H, Iijima Y, Banno N and Inoue K 2005 Cu ion planting as a technique for enhancing the mechanical, electrical and thermal bonding between Cu stabilizer and the RHQT-processed Nb3Al conductor IEEE Trans. Appl. Supercond. 15, pp 3376-79
[5] Kikuchi A, Takeuchi T, Kitaguchi H, Iijima Y, Banno N, Sakurai Y and Tagawa K 2005 Fabrication of Cu stabilizer into long-length RHQT-processed Nb3Al round wire will be presented at MT-19 September 2005 Genova Italy
[6] Bray S L, Ekin J W and Kuroda T 1993 Critical-Current Degradation in Multifilamentary Nb3Al Wires from Transverse Compressive and Axial Tensile Stress IEEE Trans. on Appl. Supercond. 3 pp 1338-1341
[7] Fukuzaki T, Takeuchi T, Banno N, Tatsumi N, Itoh K, Ogiwara H and Wada H 2002 Stress and strain effects of Nb3Al conductors subjected to different heat treatments IEEE Trans. Appl. Supercond. 12,
[8] Banno N, Uglietti D, Seeber B, Takeuchi T and Fluekiger R 2005 Strain dependence of superconducting characteristics in technical Nb₃Al Supercond. Sci. Technol. 18 284-288

[9] Takeuchi T, Iijima Y, Inoue K, Wada H, ten Haken B, ten Kate HHJ, Fukuda K, Iwaki G, Sakai S and Moriai H 1997 Strain effects in Nb₃Al multifilamentary conductors prepared by phase transformation from bcc supersaturated-solid solution Appl. Phys. Lett. 71 (1) pp 122-124

[10] Ambrosio G, Andreev N, Barzi E, Bauer P, Ewald K, Ozelis J and Sabbi G 2000 Study of react and wind for a Nb₃Sn common coil dipole IEEE Trans. Appl. Supercond. 10 pp 338-341

[11] Barzi E, Andreev N, Kashikhin V V, Turrioni D and Zlobin A V 2004 Study of Nb₃Sn cable stability at self-field using a sc transformer IEEE Trans. Appl. Supercond. 15 pp 1537-406

[12] Barzi E, Workas T and Zlobin A V 2005 Sensitivity of Nb₃Sn Rutherford-type cables to transverse pressure IEEE Trans. Appl. Supercond. 15 pp 1541-44

[13] Ambrosio G, Andreev N, Barzi E, Bordini B, Denarie C–H, Feher S, Verweij A P and Zlobin A V 2005 Measurement of critical current and instability threshold of Rutherford-type Nb₃Sn cables to be presented at MT-19 September 2005 Genova, Italy

[14] Feher S, Ambrosio G, Andreev N, Barzi E, Bordini B, Carcagno R, Kashikhin V I, Kashikhin V V, Lamm M J, Novitski I, Orris D, Pischalinikov Y, Sylvester C, Tartaglia M, Yamada R and Zlobin A V 2004 Cable testing for Fermilab’s high field magnets using small racetrack coils IEEE Trans. Appl. Supercond. 15 pp 1550-53

[15] Kashikhin V V, Andreev N, Kashikhin V S, Novitski I and Zlobin A V 2005 Magnetic and Mechanical Designs of 15T Nb₃Sn Accelerator Dipole Based on Shell-type Coil to be presented at MT-19 September 2005 Genova Italy