RHQT Nb_3Al 15-Tesla Magnet Design Study

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Abstract. Feasibility study of 15-Tesla dipole magnets wound with a new copper stabilized RHQT Nb_3Al Rutherford cable is presented. A new practical long copper stabilized RHQT Nb_3Al 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 1000A/mm^2 at 15 Tesla at 4.2K, with a copper over non-copper ratio of 1.04, and a filament size less than 50 microns. For this design study a short Rutherford cable with 28 Nb_3Al strands of 1 mm diameter will be fabricated late this year. The cosine theta magnet cross section is designed using ROXIE, and the stress and strain in the coil is estimated and studied with the characteristics of the Nb_3Al strand. The advantages and disadvantages of the Nb_3Al cable are compared with the prevailing Nb_3Sn cable from the point of view of stress-strain, J_c, and possible degradation of stabilizer due to cabling. The Nb_3Al 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 Tesla magnet, a series of tests on strand and Rutherford cables are considered.

Keywords: Nb_3Al, RHQT, Rutherford cable, High Field Superconducting Accelerator Magnet

1. Introduction

The LHC magnets are now being produced with NbTi strands as 9 Tesla dipole magnets. In the last decade, many institutions have been working to develop 10 to 15 Tesla dipole magnets utilizing Nb_3Sn strands for higher energy accelerator magnets [1, 2]. Nb_3Al strand were known to have higher compressive stress and higher axial strain tolerance than Nb_3Sn, and it was considered for accelerator magnets [3]. But it has been difficult to make a long stabilized Nb_3Al strand. Recently National Institute of Material Sciences in Japan succeeded to produce several hundred meter long stabilized Nb_3Al strands [4, 5]. The detailed characteristic parameters and production process of RHQT Nb_3Al is reported [6]. As we are preparing now to make a Rutherford cable with the newly developed Nb_3Al strand, we enumerated the tests to be done with the strand, cables and a small scale magnet, as well as a preliminary design of 15 Tesla magnets.

2. RHQT Nb_3Al Strand

The Rapid-Heating Quenching and Transformation Nb_3Al strand goes through several production processes.

2.1. Precursory Nb_3Al Strand

The present Nb_3Al strand is made by ‘Jelly Roll’ 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_3Al 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. 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.

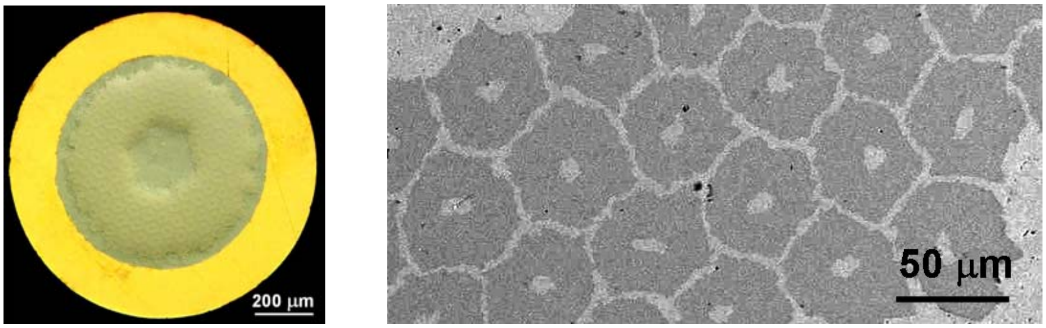

Figure 1. The cross section of 1mm diameter Nb_3Al strand and its magnified picture of filament structure.

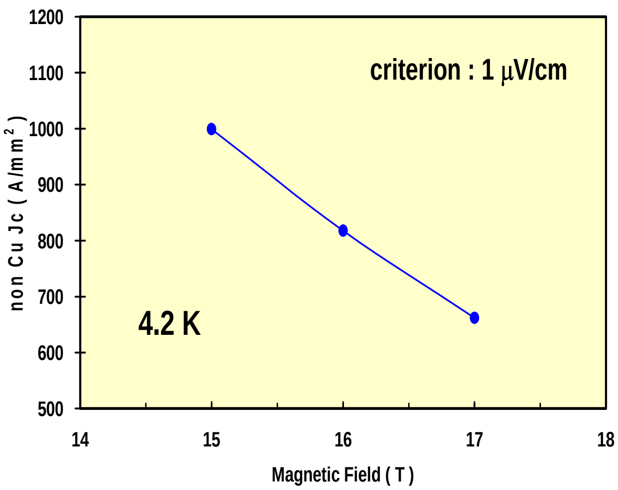

Figure 2. Short sample data measured at 4.2K.

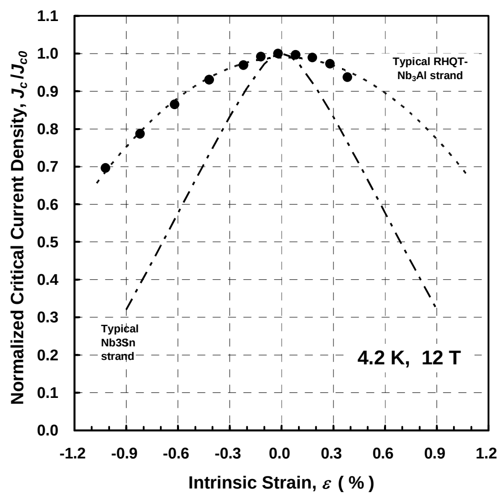

Figure 3. Stress and strain curve of RHQT Nb_3Al strand. That of Nb_3Sn is shown for comparison.

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 Nb_3Al. The A15 RHQT Nb_3Al 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/mm^2 at 15 Tesla at 4.2 K is achieved, and its I_c current is 400 A. The Nb matrix/Nb_3Al 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 [3]. Although the Nb_3Al strand can be heat treated only in 10 hours at 800 K, 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 strand in the similar gradual heat treatment modes to check the J_c value.

3. Strain and Stress of Nb_3Al Strand

The most advantageous point of the Nb_3Al over Nb_3Sn is its strength in the stress and strain problems. The experimental data on the degradation of J_c value verses axial strain and transverse compressive stress of the RHQT Nb_3Al has been reported [7-9]. The degradation of the critical current J_c at 12 Tesla at 4.2 K of RHQT Nb_3Al strand with the intrinsic strain is shown in figure 3 together with the value for a typical Nb_3Sn strand. The shape of the degradation is same for all different Nb_3Al 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 Tesla, the intrinsic strain value in the figure will be reduced to 70 % down. For the compressive stress of the strand, a low-temperature reaction Nb_3Al shows J_c decreases by 20 % at 160 MPa at 12 Tesla at 4.2 K, while ITER Nb_3Sn strand experiences same decrease at in J_c at 90 MPa [6]. We have to check this strain and stress problem at 15 Tesla with our epoxied cable.

4. Reacted Strand Tests

After heat treatment of the cable, we will extract strands and will do the short sample test on the extracted strands as well as the original round strands. Compared with Nb_3Sn strand, 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 MJR Nb_3Sn strands is reported in a previous paper [10].

5. Rutherford Cabling of Nb_3Al Strands and its Test Methods

It is planned to make a 28 strand Rutherford cable with 1mm Nb_3Al strands at Fermilab late this year. With 1 km of strand, we should be able to make about 36 meter 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 Tesla, 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 Tesla [13].
With a 20 meter cable, we will make a small race track coil magnet as a cable test based on Wind and React method. Its structure and its test results with the PIT Nb_3Sn cable is described in the other paper [13]. We will test the magnet up to its full current. With 14 kA current in the cable, the peak field in the racetrack coil will be 15 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 1.5 mm spacing between two layers.

6. Design Study of 15 Tesla Block Type Magnet

The cosine theta 15 Tesla magnet designs, mostly using Nb_3Sn strands are reported at MT-19 [15], and here we present briefly the 15 Tesla block type magnet made with Nb_3Al strands. The cross section of the 15 Tesla 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 Tesla at 4.5 K with the quench current of 10,226 A, with the maximum filed of 15.4 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_3Al cables. 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_3Al 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 Tesla with 1.9 K operation.

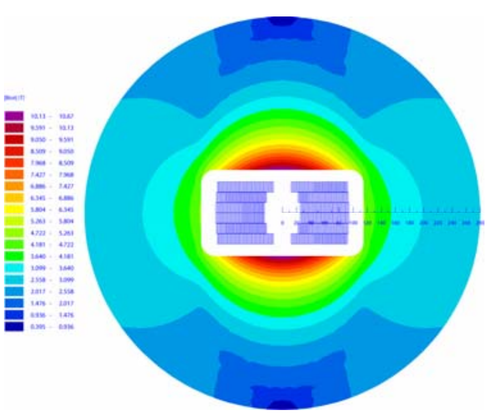

Fig. 4. Cross section of the block type RHQT Nb_3Al 15 Tesla dipole magnet, showing the saturation in yoke.

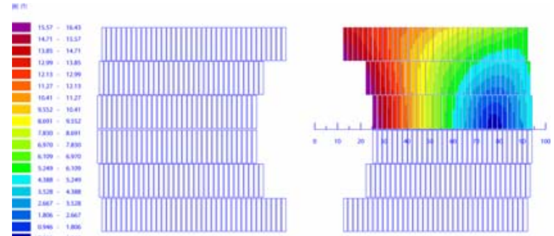

Fig. 5. Flux distribution of the 15 Tesla RHQT Nb_3Al coil.

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 modification of yoke design with holes in yoke.

7. Conclusions

In the mid-range of 15 Tesla for the accelerator magnet application, the Jc value of Nb_3Al strand has been tremendously improved due to the invention of RHQT method. And with the successful attachment of the copper stabilizer to Nb_3Al, we think the Nb_3Al strand can now be applied for the development in the magnets in this field range. We think we can expect still more improvements, in J_c and I_c values, and in strand manufacturing process. The most 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 a one year. As an application to the 15 Tesla magnets, we showed an example of a block type 15 Tesla magnet, which can be designed and constructed with the present RHQT Nb_3Al strand. Although we still have to work out on many details, including the end design, we think we can design, build and test 15 Tesla dipole magnets successfully using Nb_3Al strands.

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