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# Design Study of 15-Tesla RHQT $Nb_3Al$ Block Type Dipole Magnet

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***Abstract*—The design study of the block type 15-Tesla RHQT $Nb_3Al$ dipole magnet, and its merits over $Nb_3Sn$ magnets are presented. The copper stabilized RHQT $Nb_3Al$ strand is now becoming commercially available for the application to the accelerator magnets. A 1 mm diameter RHQT $Nb_3Al$ strand with filament size about 50 μ, non-copper Jc about 1000 A/mm$^2$ at 15 Tesla at 4.2K, copper ratio of 50 %, can now be produced over several hundred meters. The stress and strain characteristics of the $Nb_3Al$ strand are superior to the $Nb_3Sn$ strand. Another advantage is that it can tolerate a longitudinal strain up to 0.55%. The RHQT $Nb_3Al$ Rutherford cable will have less chance of contamination of the stabilizer, compared to $Nb_3Sn$ cable. These characteristics of the RHQT $Nb_3Al$ will be beneficial for designing and producing 15-Tesla dipole magnets. An example 15-Tesla magnet cross section, utilizing the RHQT $Nb_3Sn$ strand is presented. A systematic investigation on RHQT $Nb_3Al$ strands, its Rutherford cables, and building a small racetrack magnet for cable testing are proposed.**

***Index Terms*—Accelerator Magnet, Block Type Design Dipole Magnet, $Nb_3Sn$ Cable, Superconducting High Field Magnet**

## I. Introduction

THE $Nb_3Sn$ strand was developed earlier than NbTi strand, but the industrialization of the NbTi strand was pushed much harder than the $Nb_3Sn$ strand. Now the LHC magnets are being accomplished as 9 Tesla dipole magnets. In the last decade, many institutions had been working hard to develop 12 to 15 Tesla dipole magnets for higher energy accelerator magnets. At the same time, the superconductor wire industry has been busy to develop high Jc and stable conductors. Several $Nb_3Sn$ prototype magnets had been made and tested, but we have not made long practical accelerator magnets. It is expected now it will take several more years before the practical long $Nb_3Sn$ accelerator magnet will be produced and tested.

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$Nb_3Al$ strand has been known to have higher $B_{co}$ than $Nb_3Sn$ strand and can stand higher stress than $Nb_3Sn$. It has been difficult to make a stabilized $Nb_3Sn$ strand, but recently stabilized $Nb_3Al$ strands were made and tested successfully [1]. National Institute of Material Sciences in Japan succeeded to produce several hundred meter long stabilized $Nb_3Al$ strand [2]. Its detailed characteristic parameters and production process is reported in this conference [3].

Recently $Nb_3Al$ strands are being used in fusion project in the field range of 13 Tesla as CICC cables, and being tested for the inner coil of the 1 GHz NMR. Also it is being considered for accelerator magnets [4].

As we are preparing now to make a Rutherford cable utilizing $Nb_3Al$ strand, we studied the feasibility of constructing 15-Tesla Dipole magnets, and its preliminary result is reported in this paper. First the presently achieved $Nb_3Al$ strand is briefly described and the parameters of a block-type 15-Tesla magnet are presented. The advantages of the $Nb_3Al$ strand over the $Nb_3Al$ strand are described. The test procedures for producing $Nb_3Al$ Rutherford cable are enumerated.

## II. RHQT $Nb_3Al$ Strand and Rutherford Cabling

### A. RHQT $Nb_3Al$ 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 into a thin multifilamentary wire.

The Jelly Roll 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 strand only includes the bcc $Nb(Al)_{ss}$ phase and it is ductile at this stage like a $Nb_3Sn$ strand. The ductility of the whole composite is ensured to make coils and cables, like a Rutherford cable.

Next 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 with copper stabilizer is very ductile at room temperature. The cross section of the 1 mm diameter strand is shown in figure 1. The magnified picture of the filament structure is in figure 2, showing the average filament size of 50 µm.

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 measured short sample data at 4.2 K are shown in figure 3. 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. It is expected $I_c$ will be 480 A at 15 Tesla at 1.8 K. The Nb matrix/$Nb_3Al$ ratio is 0.6 and Cu/non-Cu ratio is 1.04. The detailed description of the strand production is presented at this conference [3]. Although the $Nb_3Al$ strand need to be heat treated only in 10 hours at 800 °C, the magnet coil assembly cannot be brought up to 800 °C in a short time, we have to heat up and down the coil assembly gradually. Therefore we have to test the strands in the similar gradual heat treatment modes to check the $J_c$ value and the grain size.

The short sample tests of the round as well as extracted strands will be done from few Tesla to 15 Tesla at Fermilab, investigating the degradation due to Rutherford cabling. During this test we not only test maximum $I_c$ values of the strands at different fixed field values, but we also test the stability of the strands by sweeping magnetic field at fixed current values [5]. The magnetization of the strands will be tested to estimate flux jump stability. As the $Na_3Al$ filaments are embedded in niobium not in cupper, we have to estimate cryostability of the strands. The new 3D simulation method using FEM programming has been developed and will be used extensively for the stability study of $Nb_3Al$ strand. This simulation method is presented in this conference [6].

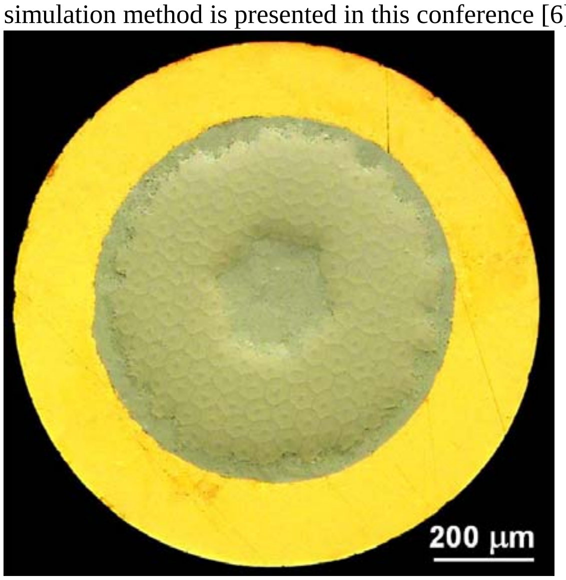


Fig.1. Cross section of 1mm $Nb_3Al$ strand. The filaments size is about 50 µm. There is a center Nb core and these filaments are imbedded in Nb matrix. The outside copper stabilizer was electroplated.

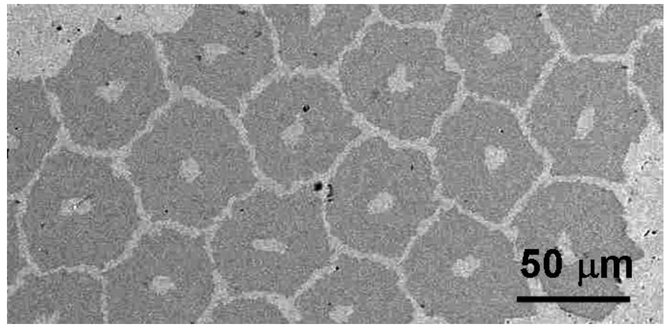


Fig. 2. Magnified picture of the filaments. The hexagonal shape of the filament is clearly seen with a Nb fine wire at each center. They are in matrix of Nb.

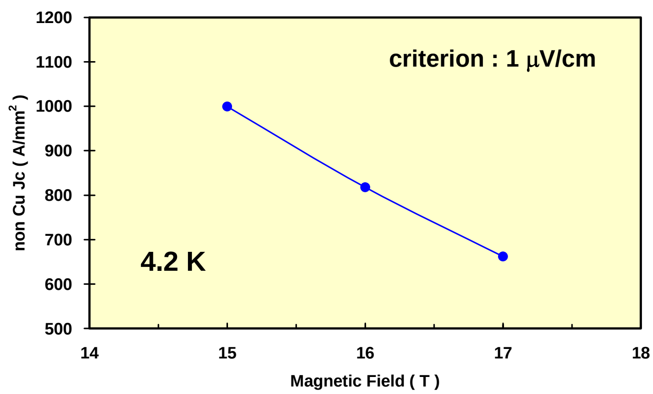


Fig. 3. Short sample data of 1 mm $Nb_3Al$ strand. Non-copper $J_c$ at 15 Tesla is 1000 A/mm$^2$ with $I_c$ of 400 A.

### *B. Strain and Stress of $Nb_3Sn$ 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, 8]. 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 4 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 [8]. We have to check this strain and stress problem at 15 Tesla with our epoxied cable.

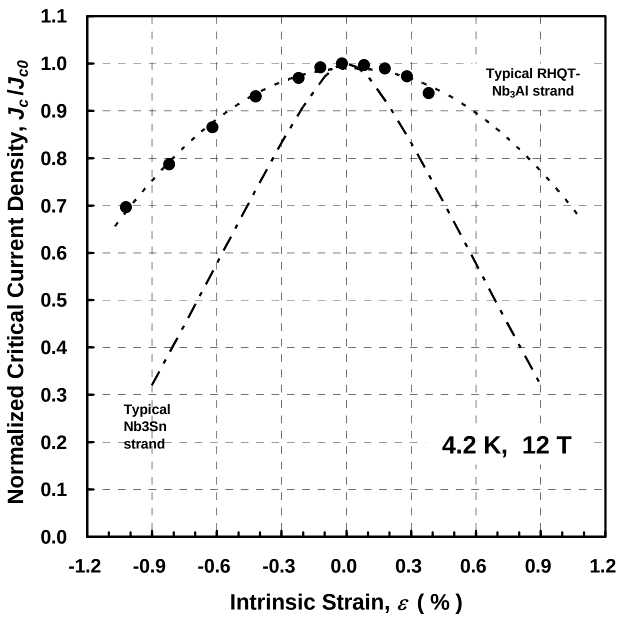


Fig. 4. Stress and strain curve of RHQT $Nb_3Al$ strand. That of $Nb_3Sn$ is shown for comparison. These are data at 12 Tesla. The corresponding data at 15 Tesla will have about 70 % less in intrinsic strain values.

### C. *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 a reacted coil with a small radius bobbin and testing again using bobbins with a smaller or a larger radius. Its test with MJR $Nb_3Sn$ strands is reported in a previous paper [9]. This will help to investigate the possible react and wind application method of RHQT $Nb_3Al$ cables.

### D. *Rutherford Cabling of $Nb_3Al$ Strands and its Test Methods*

It is planed 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 35 meter cable. A short cable itself will be tested with the flux pump method with full current at its self field [10]. 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 [11]. It is also planned to do the cable test with high transport current in the high field magnet up to 10-Tesla magnet [12].

With a 20 meter cable, we will make a small race track coil magnet, and we will test the magnet up to its full current [13]. This magnet has two layer small racetrack coils which are connected in the opposite direction and stacked tight together. With 14 kA current in the cable, the peak field in the racetrack coil will be 15 Tesla locally at the edges of coil blocks.

## III. 15-TESLA BLOCK TYPE DIPOLE MAGNET

In the last few years, design studies on 15-Tesla magnets are being discussed for the possible upgrading accelerator magnets [14, 15]. The cosine theta 15-Tesla magnet designs, mostly using $Nb_3Sn$ strands are also reported at this conference [16], Here we present briefly the 15-Tesla block type magnet made with RHQT $Nb_3Al$ strands. Its cross section is shown in figure 5. 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 flux distribution inside the coil blocks is shown in figure 6. The Lorenz force in the coil blocks are shown in figure 7. This design was done with Xroxie, using three blocks of 28 strand $Nb_3Al$ cables. The averaged total midplane stress of all block coils due to only Lorenz 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. These stress are 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.

The two dimensional stress analysis only due to the Lorenz force was done with ANSYS assuming the coil is in a rigid boundary. The Young's modulus of the coil is assumed 40 GPa. The maximum stress in the coil is 141 MPa, which is well within the tolerance of the conductor. At the maximum current, the horizontal displacement of the inner surface at the midplane is calculated 0.189 mm.

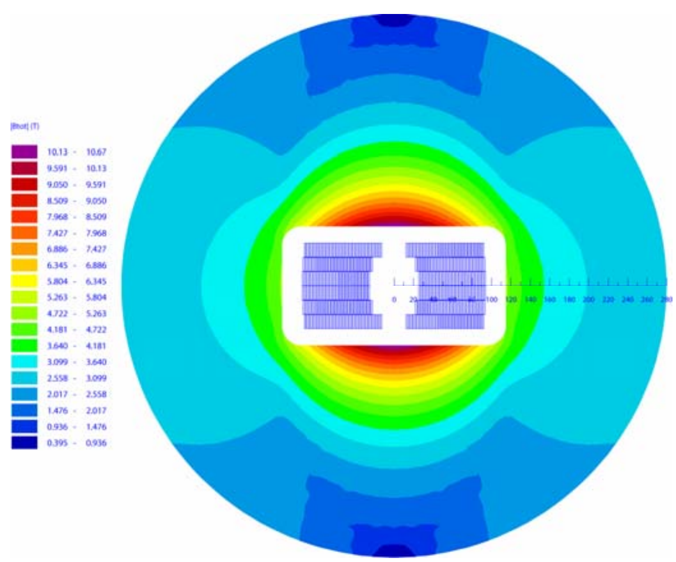


Fig. 5. Cross section of the block type RHQT $Nb_3Al$ 15-Tesla dipole magnet. The coil is held rigidly with a box type collar assembly with a central vertical column with a beam bore of 43.5 mm diameter. The horizontal distance between the innermost blocks is 50 mm. The excessive saturation of the yoke will be corrected.

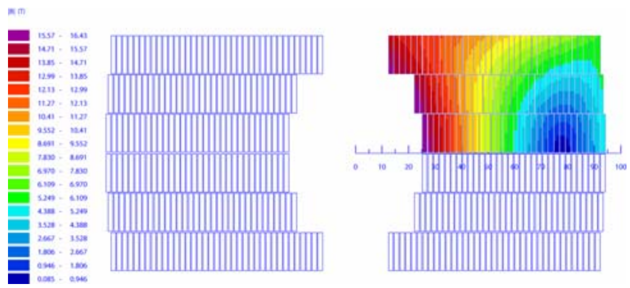

Fig. 6. Flux distribution of the 15-Tesla RHQT $Nb_3Al$ magnet at 15 Tesla.

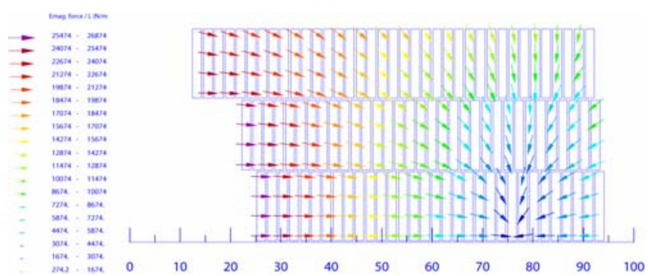


Fig. 7. Lorenz Force distribution of the 15-Tesla RHQT $Nb_3Al$ magnet coil in the first quadrant, at 15 Tesla operation.

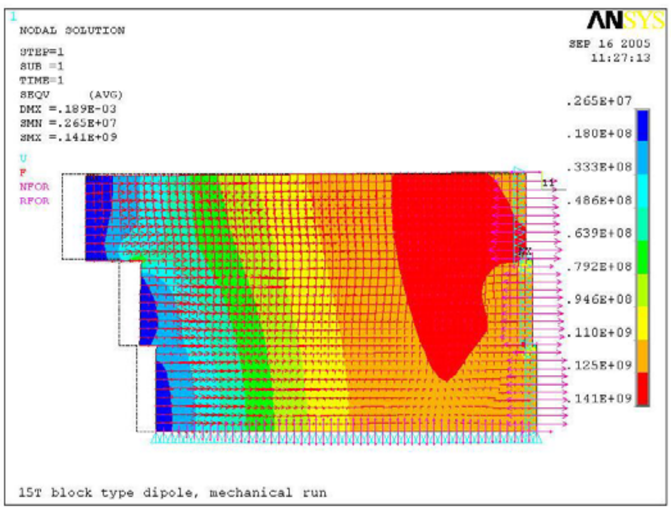


Fig. 8. Stress distribution in the 15-Tesla RHQT $Nb_3Al$ magnet, calculated with ANSYS, assuming the coil is in rigid boundaries. Stress only due to Lorenz force is shown in MPa. The displacement is shown in meter. The Lorenz force is shown with small red arrows. The black contour corresponds to cold coil geometry.

## IV. Conclusion

In the past several years the $J_c$ 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 $Nb_3Al$ precursor strand, we think the RHQT $Nb_3Al$ strand can now be applied for the development in the accelerator magnets in the 15-Tesla 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 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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