NB_3AL HIGH FIELD ACCELERATOR MAGNET R&D

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Abstract

KEK has been developing the Nb_3Al strand and cable for a high field accelerator magnet in collaboration with NIMS for many years. And also the development of subscale magnet has been started practically since last year. KEK has studied on the effect of number of filaments and matrix ratio on non-Cu Jc for last two years and also developed continuous Cu electro-plating apparatus. NIMS has fabricated the trial Rutherford cable with 27 strands successfully in collaboration with Fermi lab. And also double-layer common coil has been fabricated and tested successfully. The magnetic and mechanical design of 15 T subscale magnet has been started practically since last year, and the preparation of drawings and tools is ongoing in parallel.

INTRODUCTION

Developments of high field magnets for the LHC luminosity upgrade have been continued for many years, and Nb_3Sn conductor is the first candidate for the high field magnet because of the high current density, availability and cost. On the other hand, it is a brittle material and required careful management in terms of the design and fabrication of high field magnets. Based on the CERN-KEK collaboration for the development of high field magnets, KEK has been developing Nb_3Al conductor in collaboration with National Institute of Material Science, NIMS. That material has a better strain tolerance compared to Nb_3Sn, therefore, it could be an interesting candidate for a high field accelerator magnet, which requires a high pre-stress in order to endure a strong Lorentz force. In parallel with the conductor development, KEK has started the development program of a 15 T magnet using Nb_3Al conductor practically since last year.

This paper summarizes the present status of the development of the conductor and the design study of the 15 T subscale magnet.

STRAND AND CABLE R&D

The Nb_3Al strand is processed by a Rapid Heating Quenching, RHQ, process [1]. The unique feature of this process is the first heat treatment to convert multifilamentaly Nb/Al precursor wires into a Nb/Al supersaturated bcc solid solution. In this heat treatment, the precursors are rapidly heated up to about 2000 °C by ohmic heating, and then subsequently quenched in a Ga bath at about 50 °C. This RHQ technique enables us to fabricate 1 km-class strands, however, it is difficult to attach a copper stabilizer onto the strand. The copper stabilizer has to be attached after the RHQ operation, otherwise, the Cu would melt and react with the Nb/Al composites during ohmic heating more than 1900 °C.

The development items of Nb_3Al strand and cable are as follows; 1) improvement of non-Cu J_c, 2) development of the Cu stabilizing technique, 3) improvement of low field instabilities and 4) Cabling Rutherford cable. KEK and NIMS are developing these items to some extent in parallel.

KEK Activities

The major development items at KEK are to increase the non-copper Jc, to figure out a good stabilization method, and also to improve a low field instability. As for the first item, KEK has tried to improve the non-Cu Jc by optimizing the fabrication process, i.e., structure of cross section, heat treatment condition and ratio of area reduction after Cu stabilization. Especially, the effects of the matrix ratio and number of filaments have been studied mainly for last two years. Several wires with different Nb-matrix ratios and filament numbers were fabricated; (Matrix ratio : Filament number) = (0.6:294), (0.69 : 294) and (0.79 : 546). The previous development [2] revealed that the non-Cu Jc is increased by decreasing the Nb-matrix ratio from 1 to 0.8, however, in the strands described above, the non-Cu Jc wasn't improved as expected. In addition, there were many breakings of strand during drawing in the strand with a large number of filaments. It is found from these results that the better structures are that the matrix ratio and filament number are 0.8 and 222, respectively.

Regarding the Cu stabilization method, a special copper electroplating technique to deposit a thick Cu layer on the surface of the wire was developed. In this technique, a compound on the surface of the wire is removed by a physical and chemical methods first, and then the Ni layer in 0.5 μm thickness is deposited by Ni strike plating method in order to obtain good mechanical, electrical and thermal bonding strength between the Nb-matrix and Cu. After that, a thick Cu stabilizer is deposited by electroplating, and finally, a heat treatment to stabilize the bonding. A

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prototype, which can continuously treat a long strand with the process above, is developed. The strand in 50 m length could be fabricated successfully with the Cu thickness of 170 μ and the process speed of 1.5 m/h. Further improvement in order to increase the process speed is in progress.

KEK has also studied the improvement of low field instabilities, and fabricated the trial strand with a tantalum matrix. The measurement of non-Cu Jc and magnetization is ongoing.

NIMS Activities

The major development items at NIMS are to develop the Cu stabilizing technique, to improve low field instabilities and to make a Rutherford cable.

NIMS has developed new Cu stabilization technique using a ion-plating method [3], which is different from KEK technique. In this technique, the bare strand is pre-coated with Cu buffer layer in 1 μm thickness by using a continuous Cu ion-plating apparatus, and then thick Cu layer is deposited onto the Cu buffer layer by high speed electroplating apparatus. The ion-plating apparatus developed by NIMS successfully achieved the process speed of 4 m/min with the strand length of more than 1 km. The electroplating apparatus has developed by Hikifune corporation in Japan. The processing speed of this apparatus increases with time, and successfully reached to 7 m/h at the moment. Further improvements are in progress for both plating apparatuses.

As for the cable development, in 2006, 27 strand Rutherford cable was fabricated successfully in collaboration with Fermi lab, and some tests were performed [4]. The extracted strand shows no degradation of critical current due to the cabling. NIMS also measured cable critical currents with respect to the external field up to 11 T using FRESCA facility at CERN, and the quench currents above 9T reached to only about 85 % of the short sample limit in spite of no degradation in the extracted strand. Although the reason for this degradation in the cable is still not clear, it seems to be caused by a thermal insulation in the present sample holder.

After the successful cabling, NIMS and Fermi lab fabricated and tested a subscale common coil magnet [5]. The peak field could be reached to 9.3 T at 21.8 kA and 3.95 K, corresponding to nearly load line limit.

In order to improve low field instability, NIMS has fabricated the strand with the Ta matrix in 2007 [6]. In this strand, the low field instability at 4.2 K was apparently improved by using a Ta barrier for the interfilament matrix of precursor. Following this success, another strand with the Ta matrix has been fabricated and tested. This strand has almost the same structure but a Cu ratio is decreased from 1.0 to 0.6, aiming for the increase of the critical current. The study for this strand is ongoing.

MAGNET

Design

Basic Concept Following the successful fabrication of the subscale common coil magnet in Fermi lab described in the section , KEK has started the high field magnet development with Nb_3Al practically since 2007, in parallel with the strand and cable development. The first goal of the development is to fabricate 15 T subscale magnet for demonstrating feasibility of high field magnet with Nb_3Al.

The design of the Nb_3Al subscale magnet is based on three following concepts. The first one is to adopt a shell structure, which is developed by LBNL because of the features of easy assembly and disassembly. The second concept is to adopt a common coil configuration in order to maximize the peak field in the coil. Compared with a block dipole configuration, the support structure for this configuration could be simplified because the profile of the Lorentz force is simpler than that of a block dipole configuration. The third concept is to make use of existing Nb_3Sn coils as back up coils. This hybrid coil configuration enables us to save the conductor length of Nb_3Al. These Nb_3Sn coils are supposed to be SC-15 and 16 which were fabricated at LBNL [7], in practice.

2D Magnetic Design First, the basic parameters in terms of magnetic design were optimized using OPERA 2D, the number of strands in the cable, the yoke diameter, the numbers of layers and turns of Nb_3Al coils. Fig. 1 illustrates the result of the magnetic design. This design consists of three Nb_3Al coils with 2 layers and 15 turns and two Nb_3Sn coils of LBNL. The Nb_3Al coil placed at the center of the magnet is a two-layer common coil, and other two Nb_3Al coils are usual double-pancake coils. In this magnetic design, the yoke is 20 cm away from the coils for installing coil support structures. This model assumes the rectangular cable with the 27 strands, and the width and the thickness are 14.2 mm and 1.78 mm, respectively. The critical current of the strand is expected to be 400 A at 15 T, 4.2 K, which is based on the results of F3 strand [6]. The peak field is expected to be 14.3 T at 12.3 kA and 4.2 K.

2D Mechanical Design Based on the 2D magnetic design parameters, 2D mechanical model was designed using ANSYS. Fig. 2 shows the ANSYS quadrant model around the coil packages for the stress distribution analysis. This design concept is based on the SD-01 magnet which was developed by CEA Saclay [8]. In order to uniform the stress distribution in the coils after the excitation up to the peak current, the configuration of G10 spacers between coils is modified in such a way that the only coil part is covered with the spacer in the central common coil as shown in Fig. 2.

In the shell structure, most of the pre-stress required to react the Lorentz force is provided by the thermal contraction of the Al shell, which is much higher than other materials in the magnet. The pre-load by the thermal contraction

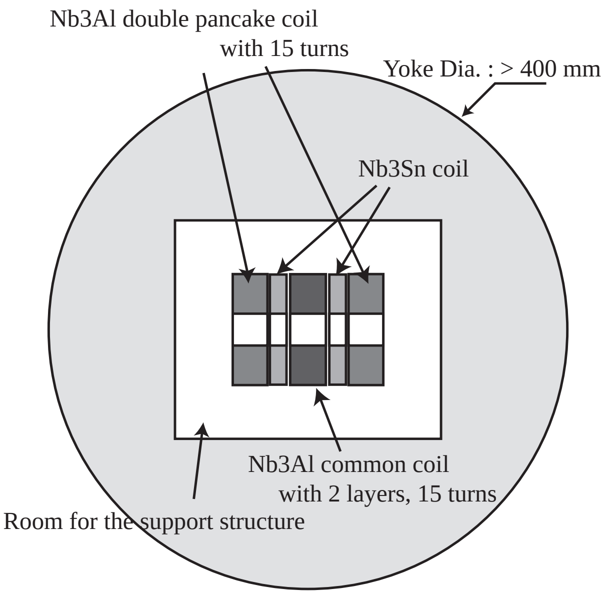

Figure 1: Magnetic design parameters of 15 T subscale magnet with Nb_3Al.

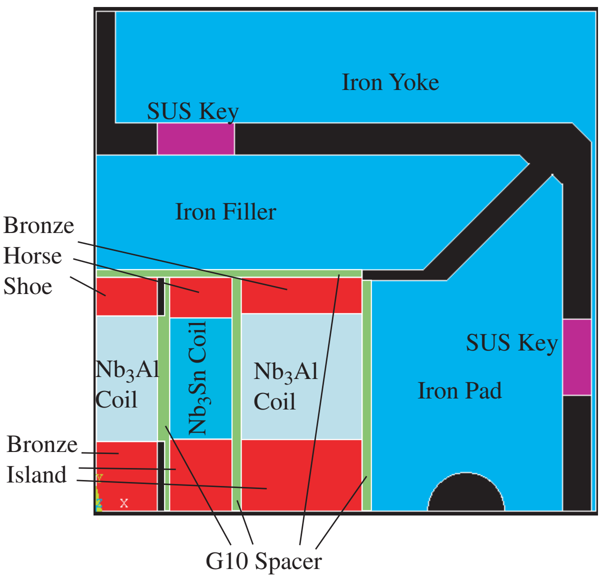

Figure 2: The quadrant ANSYS model of mechanical design.

mainly depends on the thickness and the diameter of the shell. Fig. 3 shows the relationship between the shell thickness, the yoke diameter and the pre-stress at room temperature, which is required to balance the Lorentz force with the pre-stress in the coil after cooling down to 4.2 K. Concerning the magnetic design results and the constraint of the test facility in KEK, we chose the shell thickness of 42 mm and the yoke diameter of 480 mm.

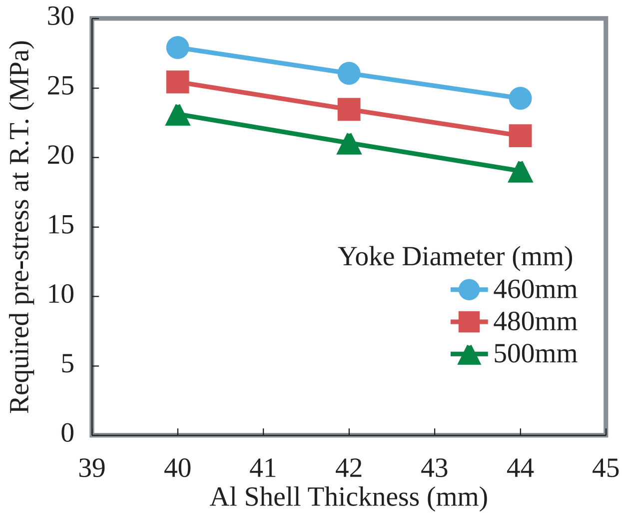

Figure 3: Relationship between the shell thickness, the yoke diameter and the pre-stress at room temperature.

Bladder Test

A bladder is an essential component in the pre-loading process at room temperature [9]. The four bladders were fabricated in Japan, and the destructive tests are performed using the test tools of LBNL. Two of four bladders could not be set in the test tools, because the blocks to feed a water into the bladder were welded in slightly wrong direction. The new fabrication process adjusting the welding tolerance would be performed next time. Other two bladders could be put in the test tools and pressurized with water. The first bladder had a spot leak at one corner just after reaching the pressure of 10000 psi. The bladder expanded up to 2.1 mm from 0.3 mm in thickness at that point. The second bladder could be pressurized up to 10000 psi with 2.1 mm in thickness. And, during the second pressurization in which the bladder was allowed to expand more than 3 mm in thickness, the bladder bursted at the welded edge near the block at 7200 psi and 3.1 mm in thickness, as shown in Fig. 4. This burst was typical and similar to one happened in many bladders which were fabricated and used at LBNL. These results indicate that the bladders made in Japan could be used for the practical magnet fabrication, although the thickness after pressurization should be controlled properly below 1 to 2 mm.

SUMMARY

High field superconducting magnets with Nb_3Al conductor is being developed in KEK for the LHC luminosity upgrade. The development of the conductor is performed in collaboration with NIMS and FNAL. In order to improve the non-Cu Jc, KEK has been optimizing the structure of the strand and the fabrication process for the high field magnet, and the matrix ratio and the number of filaments could be almost optimized from the test results of several

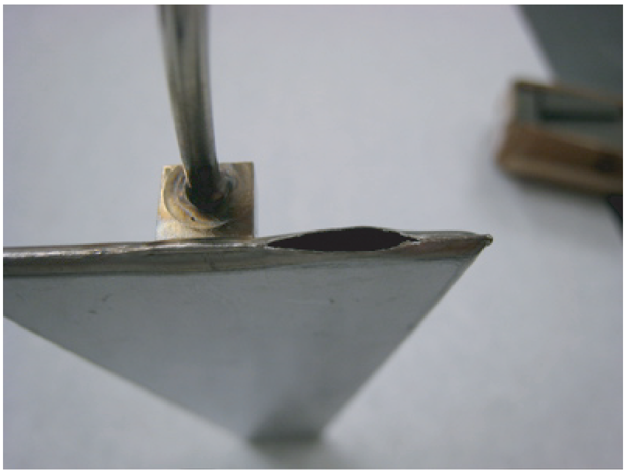

Figure 4: Bursting edge of the bladder.

strands with different structures.

The continuous Cu stabilizing techniques were developed successfully by both KEK and NIMS with their own method. As for the low field instability, it is found that Ta barrier between filaments could prevent from flux jumps below 4 T at 4.2 K. The trial fabrications of Rutherford and rectangular cables were carried out, and the test results of the strand extracted from the first cable show almost no degradation due to the cabling.

The subscale common coil magnet using this cable was fabricated and tested successfully in FNAL. The peak field could reached to 9.3 T at 21.8 kA and 3.95 K. The development of 15 T small magnet with Nb_3Al has been started practically since last year, and the 2D magnetic and mechanical design have been almost finished. As a part of preparations of fabrication tools, the prototypes of the bladder were fabricated in Japan and successfully tested in LBNL.

Aiming to complete the fabrication of 15 T subscale magnet in 2010, the preparation of the magnet parts is now underway. New two 1 km - class Nb_3Al strands are fabricating, and the cabling of these strands will be performed in this Autumn. The detail design and the fabrication of the coil parts are also ongoing, and the winding of the first coil will be started hopefully at the end of 2008.

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