Design of a High Field Nb_3Al Common Coil Magnet

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Abstract—**A high field Nb_3Al common coil magnet is under development as an R&D of "Advanced Superconducting Magnets for the LHC Luminosity Upgrade", in the framework of the CERN-KEK cooperation program. The goal of this research is to demonstrate the feasibility of high field magnet wound with Nb_3Al cable. The common coil approach and the shell-based structure were adopted in the design of this magnet. Besides three Nb_3Al coils, two Nb_3Sn coils were included to increase the peak field of the whole magnet. The two types of coils were designed with different straight lengths to reduce the peak field of the Nb_3Sn coils. The peak fields of the Nb_3Al and Nb_3Sn coils are 13.1 T and 11.8 T respectively. An aluminum shell together with four aluminum rods applies stress to the coils to overcome the Lorenz force during excitation. Two different support structures for the superconducting coils were introduced in this paper. The development status is also presented.**

Index Terms—**Common coil, high field magnets, Nb_3Al, superconducting magnets.**

I. Introduction

An R&D program of advanced superconducting magnets for the LHC luminosity upgrade has been carried out since 2006, in the framework of the CERN-KEK cooperation program. It aims to develop high field superconducting magnets expected in the LHC luminosity upgrade. The first stage (2006–2008) had progressed in focusing to establish Nb_3Al superconductor and cable technology, to prepare for the high field magnet application. At the second stage (2009–2011), together with the continuous R&D of Nb_3Al conductor and cable, an Nb_3Al common coil magnet will be fabricated, to demonstrate the feasibility of high field magnet wound with Nb_3Al cable, and also as an R&D for the advanced structure of high field magnets.

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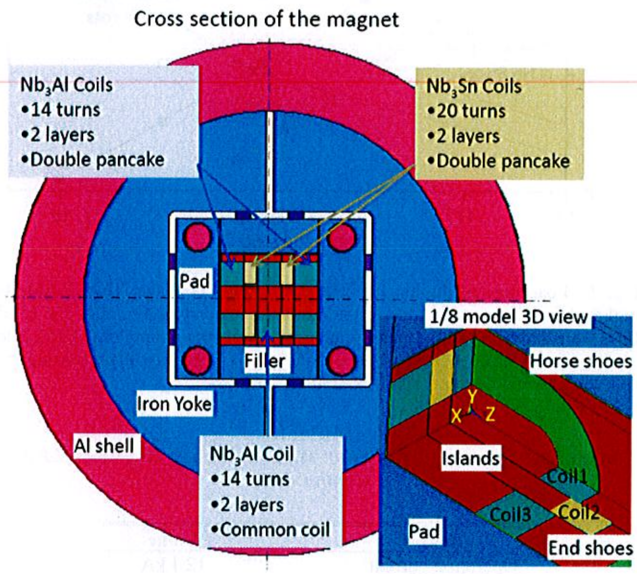

Fig. 1. Structure of the Nb_3Al common coil magnet.

The design of our Nb_3Al high field magnet has been started from 2007, under the collaboration with LBNL. The common coil approach and the shell-based structure were adopted, to generate a high magnetic field with a reasonable quantity of the superconducting cable, and to simplify the fabrication and assembly processes of the magnet. Besides the three Nb_3Al coils, two Nb_3Sn coils were also included in the magnetic design to further increase the peak field of the whole magnet. The original 2D design was presented in [1]. This paper presents the detailed 3D design, some new modifications and the development status.

II. Magnetic Field Design

The common coil approach [2], [3] was adopted in the magnetic field design. There are totally five superconducting coils, three Nb_3Al coils and two Nb_3Sn coils. The two Nb_3Sn coils (developed by LBNL, coil 2 in Fig. 1), wound with double pancake structure, help to increase the peak field of the whole magnet, which located at the center of the Nb_3Al coils. For the three Nb_3Al coils, two of them (coil 3 in Fig. 1) are wound with double pancake structure. The other one (coil 1 in Fig. 1) is wound with the common coil approach. The two kinds of coils were designed with different straight lengths, to reduce the peak field at the end of the magnet, which located at the inner boundary of the Nb_3Sn coils. For the Nb_3Al coils, the overall outer length is 200.5 mm; the width and the height are 100.5 mm and 30.8 mm respectively (14 turns per layer and 2 layers per coil). The peak field is 13.1 T, located at the center of the straight part. For the Nb_3Sn coils, the overall length is 252.9

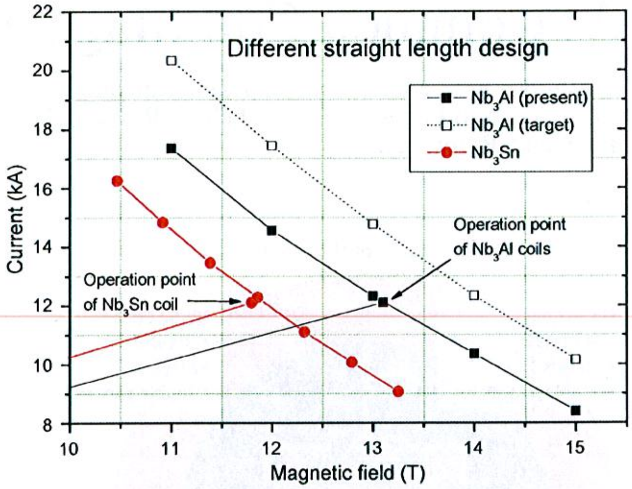

Fig. 2. Load lines of the magnet. The critical current of the Nb_3Al cable is higher than Nb_3Sn cable due to the more strands and larger area (The solid lines were derived from the measurement results of strand samples [4], [5]. The dot line shows the target critical current of the Nb_3Al cable with decreasing the Cu/Non-Cu ratio from present 0.96 to 0.75).

TABLE I
MAIN DESIGN PARAMETERS OF THE MAGNET AND THE Nb_3Al CABLE & CONDUCTOR

Item	Value
Operation current	12.1 kA
Peak field at the coils	13.1 T
Stored energy	71.8 kJ
Inductance	0.97 mH
Magnet Length	740 mm
Shell Dia.	680 mm
Nb_3Al Strand Dia.	1 mm
Cu/Non-Cu ratio	0.96
No. of Stands	28
Cable dimension	13.93*1.84 mm^2
Nb_3Sn Strand Dia.	0.7 mm
No. of Stands	20
Cable dimension	7.88*1.27 mm^2
Nb_3Al Coils No.	3
Turns No. per layer	14
Layers No. per coil	2
Nb_3Sn Coils No.	2
Turns No. per layer	20
Layers No. per coil	2

mm; the width and the height are 100.5 mm and 16.9 mm respectively (20 turns per layer and 2 layers per coil). The peak field is 11.8 T, located at the end part, inner boundary of the Nb_3Sn coils. Fig. 2 shows the load lines of the magnet. The main design parameters of the magnet and the Nb_3Al cable & conductor are shown in Table I.

Table II and Fig. 3 show the magnetic force distribution of the coils during excitation. For the coil 1, opposite direction magnetic forces are applied to the two layers, which will strongly divide the coil 1 into two parts, damaging the insulation materials between the two layers, and also cause a large movement of the Nb_3Al cable. For the coil 2 and coil 3, the magnetic forces are trying to separate the coils with islands and horse-shoes. All these forces should be overcome to protect the insulation materials from being damaged and minimize the movement of the superconducting cable during excitation.

TABLE II
MAGNETIC FORCE OF THE COILS WITH OPERATION CURRENT OF 12.1 kA
(1/8 MODEL, UNIT: KN)

Direction	X	Y	Z
Coil 1	106	12	10
Coil 2	199	118	31
Coil 3	-61	106	62

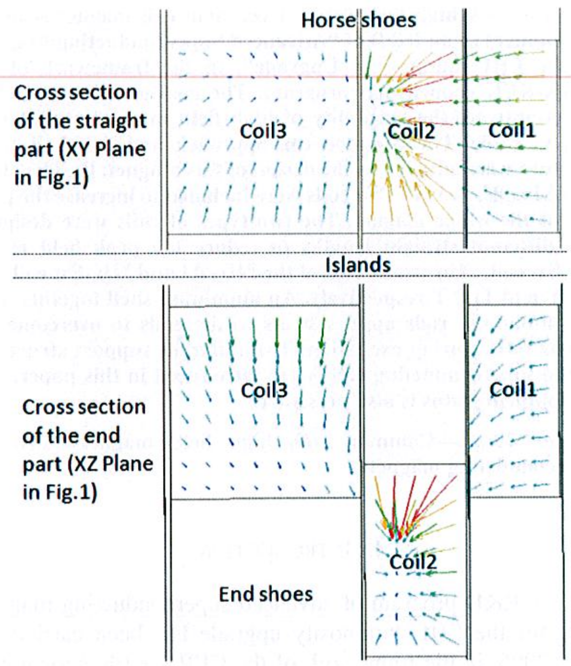

Fig. 3. Magnetic force distribution at the straight part and end part.

III. MECHANICAL DESIGN

To simplify the future assembly processes, the shell-based structure was adopted in the mechanical design of the magnet [6]. The thermal contraction stress of the aluminum shell and four aluminum rods, together with the pre-stress applied at the room temperature, overcome the Lorenz force during excitation, to prevent the separation of the coils from the insulation materials and the surroundings. With the assumption that the epoxy can sustain separation stress of 20 MPa at the low temperature, the pre-stress in three directions were optimized. In horizontal direction, the pre-stress is applied with the bladder inserted between the yoke and the pad. The required magnitude is designed to be around 50 MPa (by adjusting the shell thickness or the support structure of the coil), for an easy and safety operation in the future assembly processes. In vertical direction, the pre-stress is automatically applied by the deformation of the aluminum shell during the bladder operation in the horizontal direction. In axial direction, around 130 KN pre-stress (for each rod) is applied by tightening the nuts at the end of the aluminum rods. Extra 91 KN contraction force will be applied after cool-down. All these efforts are made to ensure the contact pressure around the coils larger than -20 MPa during excitation (minus-separation; plus-compression).

The magnitude of the pre-stress in axial direction is mainly determined by the separation stress between the coils and the

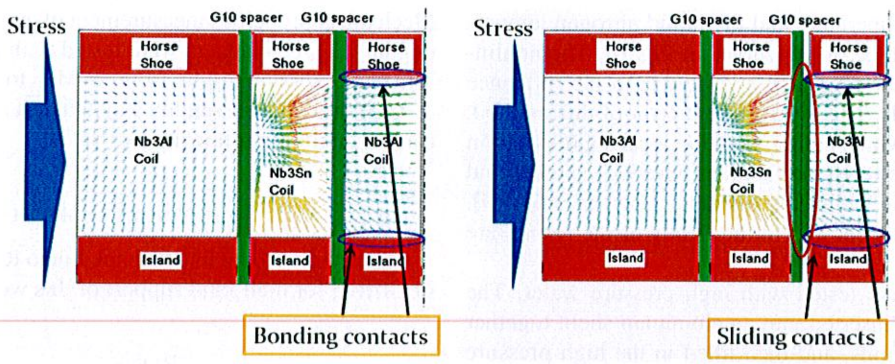

Fig. 4. Two types of support structures for the coils (XY plane in Fig. 1). Left: A common support structure. Sliding contact between the coil and surroundings is not required, but most of the stress transferred to the horse shoes and islands. Right: A special support structure to increase the transfer efficiency of the stress, but the sliding contact is required.

islands at the end of the magnet, especially for coil 1 and coil 3, the different straight length design enhance the separation stress of the two coils, as shown in Fig. 3. Four aluminum rods with the diameter of 36 mm were designed to overcome this stress.

The magnitude of the pre-stress in horizontal direction is strongly related with the support structure of the coils and the shell thickness of the magnet. With a thinner aluminum shell, the force provided during cool-down is smaller, so the higher pre-stress is required, and vice versa. In a traditional common coil approach, as shown in Fig. 4, if no special feature is included in the coil design, most of the force coming from the outer shell will be intercepted by the islands and horse-shoes, characterized by a more rigid material than the windings. In other words, the stress is not efficiently transferred to the coils. As a result, the thicker aluminum shell would be required, but with this method, the coil winding and magnet assembly will be carried out in the most common and easy way.

Another choice is to design some special support structures for the coils, to increase the efficiency of the stress transfer, as a result, to reduce the thickness of the aluminum shell. However, a cost we should bear is that the coil fabrication and magnet assembly processes become complicated. The sliding contact between the coils and the surroundings is required, and also, stress concentration is easy to occur at the boundary of the coils.

As an R&D program, we will try both of the methods in our magnet assembly processes. A large thickness aluminum shell was already ordered for the first method. Several test experiments will be carried out for the two methods, and the final behaviors will be compared and analysed.

To minimize the thermal stress in the coil packs during heat reaction process, the islands, horse shoes and end shoes are fabricated with aluminum bronze, whose thermal expansion coefficient is very close to the superconducting coils.

IV. Development Status and Schedule

By using a strain gage method [7]–[9], a mechanical properties measurement system was set up for an Nb_3Al coil sample, which was cut from a racetrack coil fabricated by Fermi Lab. [10]. The measurement system includes pressure pump, load cell, cryogenic vessel, strain gages, bridge box, data acquisition system and etc. Several strain gages were attached to the outer surface of the coil sample, to measure the strain under certain load application at the room temperature and the liquid nitrogen temperature, as shown in Fig. 5. With this method, the Young's modulus, Poisson's ratio and thermal expansion coefficient of the sample can be obtained (For the thermal expansion coefficient measurement, a reference sample with known properties should be measured together with the test sample, by using the same type of strain gages).

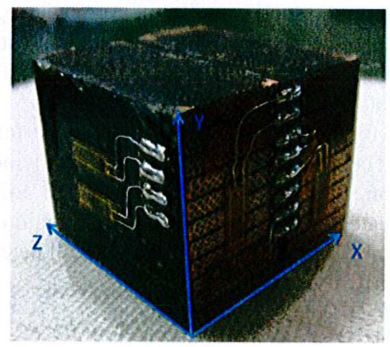

Fig. 5. Strain gages were attached to the Nb_3Al coil sample, to measure its mechanical properties.

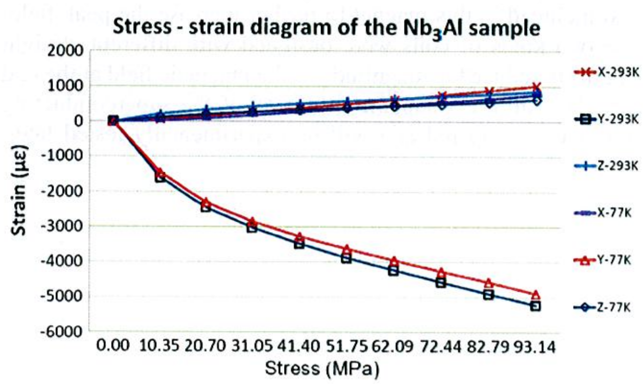

Fig. 6. Stress-strain diagram of the Nb_3Al coil sample.

A preliminary measurement was done. Totally 12 strain gages were attached to the Nb_3Al coil sample, 4 in each direction. The load was applied in the Y direction. The stress-strain diagrams in three directions were measured from 0 to 93 MPa both at the room temperature and the liquid nitrogen temperature. The results are shown in Fig. 6, from which we see that for the Nb_3Al coil sample, the difference of the Young's modulus between the room temperature and the liquid nitrogen temperature is very little (slope of the curves in Fig. 6). The nonlinearity at the low stress region should be due to the influence of insulation materials. The measurement error of this method, generally speaking, which comes from the local sources, strain sensing sources, gage resistance sources, interface sources and instrument sources, is within the tolerable range of $\pm 5\%$ [9]. The detailed measurement and further study of the results are ongoing.

Three bladders were tested with high pressure water. The bladders were firstly inserted into an aluminum shell, together with the yoke and shims, and then filled in the high pressure water. Two of them burst at the welding boundaries with the pressure of 69 MPa and 103 MPa. The other one burst at the connector between the bladder and the water tube with a quite low pressure during the air removing period. The strain variation of the aluminum shell was also measured during the bladder test, and compared with the ANSYS simulation results. It shows that the simulation results with friction coefficient 0.2 fit the experimental data well.

The cable for the first Nb_3Al coil has been fabricated and wrapped with ceramic insulation material. The winding process will start soon. For the following two Nb_3Al coils, the cable will be fabricated in the end of 2009 and the mid of 2010. The magnet assembly and the test experiment will be carried out in the following two years.

V. Conclusion

An Nb_3Al common coil magnet with the peak field of 13.1 T was designed and under development. Two Nb_3Sn coils were also included in this magnet to further increase the peak field. The two kinds of coils were designed with different straight lengths to reduce the magnitude of the magnetic field at the end part. Two different support structures of the superconducting coils were compared and will be experimentally tested later. Mechanical properties measurement of an Nb_3Al coil sample is ongoing. Three bladders were tested with high water pressure. The burst pressure differs from 69 MPa to 103 MPa.

The fabrication, assembly and final test of this magnet will be carried out in the following two years.

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