DEVELOPMENT OF A 10 T Nb_3Sn TWIN APERTURE MODEL DIPOLE MAGNET FOR THE CERN LHC

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As part of the magnet development programme for the proposed Large Hadron Collider LHC at CERN, an experimental 1 meter long twin aperture dipole magnet is under construction using a Nb_3Sn superconductor in order to attain a magnetic field of at least 10 tesla at an operating temperature of 4.2 K. The paper reports on the design aspects of the magnet and the present state of development is presented.

Introduction

The proposed colliding energy of 16 TeV for a new hadron collider LHC in the LEP tunnel at CERN [1] can only be attained if 10 T dipole magnets are feasible and provided they can be made in industry. In collaboration with a few European laboratories and industries a magnet development programme is carried out to investigate both the NbTi/2 K as the Nb_3Sn/4 K alternatives. However, the main efforts focus on the NbTi/2 K route. This implies that the magnet technology based on NbTi superconductors is applied by which the coils operate at a reduced temperature of about 2 K, instead of the usual 4.2 K, in order to obtain a sufficiently high current density.

When the present "state-of-the-art" of the Nb_3Sn wire production, the cost of the windings and the limited experience with Nb_3Sn magnet technology in the industry is considered, then it is obvious to use NbTi. At this moment Nb_3Sn is still not a reliable and cost efficient solution for the major part of the LHC magnet system. This means that, with exception of a few specific magnets, the LHC main dipole coils will be made with NbTi. But, on the other hand, when using NbTi it will hardly be possible to attain a clear and stable 10 T operation of the entire string of magnets. Especially those sections which are exposed to an increased level of radiation are critical. So, at the moment, it is uncertain whether a clear 10 T mode of operation can be realized for the magnets since the critical current density at 2 K of industrially made NbTi is not sufficient for that.

On the contrary, a magnetic field level of 10 T or even higher could be realized within the present LHC dipole geometry when using Nb_3Sn technology and at this point we touch the aim of this work. The magnet development project about which we report here deals with to use a Nb_3Sn superconductor at 4.2 K and to design and construct an experimental dipole magnet for 10 T. For this a 4 years R&D programme was started in 1988, in the framework of a cooperation agreement with CERN, by the Applied Superconductivity Centre at the University of Twente and NIKHEF, the National Institute for Nuclear and High Energy Physics, in collaboration with ECN, HOLEC and SMIT WIRE. In this project the efforts mainly focus on the highest possible field within the restrictions of the LHC coil design using the best available Nb_3Sn conductor.

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Magnet layout and main parameters

The restricted space available in the LEP tunnel for LHC requires to combine both beam tubes into a so-called "2-in-1" or twin aperture magnet. Figure 1 provides a schematic view of this type of magnet (construction details and cryostat parts are not shown). The criteria which have led to this geometry are the field of 10 T on the beam, the aperture size of 50 mm and the intra beam distance of 18 cm as restricted by the size of the LEP tunnel. The reference design based on this, shows a 2-shell coil system with graded current density, surrounded by a single force-retaining structure which consists of laminated clamping collars, a vertically split and laminated cold iron yoke and an outer shrinking cylinder that handles the major part of the forces. The main parameters of the coil system are given in Table 1.

The coil support has to provide a rigid structure and a sufficiently high dimensional accuracy to guarantee the field quality during the entire operation cycle. Clamping of the coils in LHC dipole magnets is obtained by a combined action of collars, yoke and the outer cylinder in a mechanically hybrid support structure [3]. About 30 % of the force F_x in the horizontal plane of 4.6 MN per meter at 10 T is taken by the collars and the major part of 70 % is taken by the outer cylinder. The stress level in the windings can go up to about 140 MPa. More information on the magnet technology for LHC can be found in references [1-3].

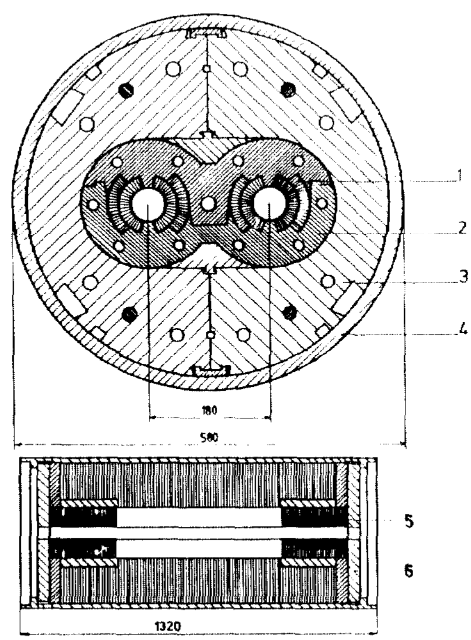

Figure. 1 Cross and longitudinal sections of a 10 T twin aperture LHC dipole magnet showing: (1) coils, (2) collars, (3) cold iron yoke, (4) outer shrinking cylinder enclosing the cold magnet parts, (5) coil head sections, (6) end-flange, end-plates.

Table 1.			
Main parameters of the 10 m long dipole magnets of the LHC reference design.			
nominal magnetic field	=	10.0	T
max. field in layer 1	=	10.2	T
max. field in layer 2	=	8.7	T
full magnetic length	=	9.5	m
coil inner diameter	=	50	mm
coil outer diameter	=	122	mm
distance between beams	=	180	mm
overall mass	=	18	tons
cold mass	=	15	tons
mass of superconductor	=	600	kg
stored energy at 10 T	=	684	kJ/m
operating current	=	16	kA
maximum Lorentz forces:			
in x-direction	=	4.6	MN/m
in y-direction	=	-1.2	MN/m
in z-direction	=	0.17	MN/m

Model magnets

The various model magnets now being built [4] have a 1:1 scale magnet cross-section and a reduced length of 1 meter. With NbTi the magnet technology is less difficult and based on the experiences obtained with the HERA magnets. Two 1 meter single aperture 8 T NbTi model magnets were built by ANSALDO and tested up to 9.3 T at about 2 K. Four 1 meter twin aperture 10 T NbTi model magnets are now in production in the European industry at HOLEC (NL), ELIN (Au), Ansaldo (I) and Jeumont Schneider (F). A 9 m long NbTi model magnet is made by ABB to gain experience with long twin aperture magnets using the existing HERA tooling, coil geometry and conductors. The next step, which will start this year, is to built a few 10 meter long prototype magnets to perform a first string test in 1992.

The Nb_3Sn route is developed within two projects. First, CERN and the ELIN company in Austria made a 1 meter mirror coil and a complete single aperture Nb_3Sn dipole model magnet which achieved a maximum quench field of 9.5 T [5]. The second project is the one also presented here [6]. For the success of the Nb_3Sn programme the properties of the available Nb_3Sn conductors is essential.

Nb_3Sn conductor development

A field level of 10 tesla maximum requires, according to the LHC magnet reference design, a development of conductors with an average current density of at least 650 A/mm^2 at 11 T (≈790 A/mm^2 at 10 T) and 90 % of the critical current. Moreover, for the stability and quench behaviour a copper part not less than 50 % is asked for. To obtain the required field quality and to limit the field errors due to magnetization effects, the filament size should be well below 10 μm. In Table 2 a survey of typical critical current densities of Nb_3Sn wires which are more or less available is given. We can conclude that the combination of a J_c>1550 A/mm^2 at 10 T and D_{fil}<10 μm does not exist with the present state of the Nb_3Sn wire development.

The bronze type of conductors (the first 4) have the advantage of being available on an industrial scale and they have fine filaments, but the wires are less performing in terms of critical current density. The LHC specification can only be reached by reducing the amount of copper in the wire section to 25-30 % instead of the 50-60 % and even then the margin is very small. The first LHC model magnet was made with this material [5]. A field above 10 T is only possible when the volume of the windings is increased by using a 4 layer coil.

Table 2.

Typical critical current densities J_c(non Cu part) and effective filament size D_{fil} in a few Nb_3Sn wires of which a (small) production exists (approximate values taken from data sheets, wire diam. 1mm)

manufacturer	$J_c$nonCu[A/mm^2] at 10 T	D_{fil} [μm]
VAC (1)	750-850	3-5
Hitachi (1)	800-850	3-5
Furukawa (1)	400-500	3-5
Sumitomo	700-800	3-5
Showa (4)	1500-1600	45-75
TWCA (2) (1)	1400-1500	40-50
TWCA (3) (1)	700-800	10-15
ECN (5)	2000-2100	20-40

(1) industrial fabrication exists of wires and cables,
(2) wire optimized for high current density,
(3) wire optimized for small filaments at moderate J_c,
(4) not available in large quantities, no cables,
(5) production for special projects only, including cables.

The average current density in the ECN type powder method wire [8] is, with the same amount of stabilizing copper, about a factor 2 higher than in the bronze type of Nb_3Sn wires. However a further development of this type of wire is needed to get fine filaments. Wires with 36 and 192 filaments were made in a production quantity of about 500 kg and double-stack wires with up to 1332 filaments, which provides 10 μm filaments, have already been made on a laboratory scale. Two prototype LHC cables, having strands with 192 filaments, were tested recently [9]. As an example, a cross section is shown in figure 2. This cable for the outer coils shows an excellent performance and has a critical current of 30 kA at the working point of 8.7 T in the LHC reference design which is about 90 % above the nominal operating current. This result clearly demonstrates the high potentials of the Nb_3Sn powder method conductor.

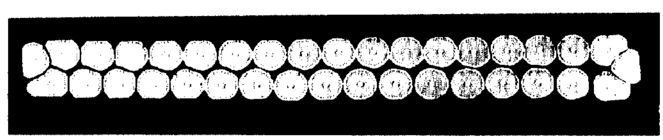

Figure 2. Photograph of an LHC cable with ECN-type Nb_3Sn wires; 36 strands 0.90 mm diameter, 192 filaments, 55% Cu matrix, size = 1.45/1.77×16.40 mm^2.

Development programme Nb3Sn model magnet

The research and development program for the Nb_3Sn LHC model magnet includes an integral design study of the dipole magnet components in order to get the best possible solution for the Nb_3Sn magnet within the boundaries set by the general LHC magnet specifications. The starting-point is to design a magnet for 10 T nominal field and a target field of 11.5 T based on a Nb_3Sn conductor with a J_c of 1500 A/mm^2 at 10 T, 50 % Cu and a filament size as small as possible.

Coil section and conductor layout. The arrangement of the conductors in the coil section was reconsidered in order to obtain a safe design for 11.5 T. Various distributions were evaluated [7]. An example of a possible conductor distribution is shown in figure 3. The parameters of the two cables as required for the inner and outer layers are given in Table 3 for the 11.5 T design in comparison to the reference of 10 T. Note that the widths of the both cables are different and that the total built-up has increased with 5 mm to obtain 11.5 T maximum.

Table 3.

Parameters of Nb_3Sn cables for the inner and outer coils respectively (1 m magnet). (I) reference design for 10 T; (II) design for 11.5 T.

		(I) 10 T reference		(II) 11.5 T design	
layer	[-]	first	second	first	second
thin edge thickness	[mm]	2.19	1.47	1.98	1.54
tick edge yhickness	[mm]	2.69	1.79	2.47	1.93
bare width	[mm]	16.8	16.8	21.7	17.4
strand diam.	[mm]	1.35	0.99	1.26	0.98
percentage Cu	[%]	50	50	50-60	50-60
number of strands	[-]	24	36	34	35
RRR value	[-]	>100	>100	>100	>100
cable pitch	[mm]	<120	<120	<150	<150
cable length	[m]	4x25	4x40	4x25	4x40
nominal current	[kA]	≈16@10.2T	@8.7T	≈17.7@11.9T	@9.6T
critical current	[kA]	>17@11T	>18@8.5T	>20@12T	@10T

Coil support structure. The increase of the outer radius of the coils with 5 mm is compensated by using a shrinking collar by which the lost space, taken by the axial pins to close the usual collars, is used for extra strength. A short 10 cm model to test the shrinking collar design is now under construction. Results are compared with ANSYS calculations. The input of forces came from 3-D calculation of the magnetic fields using TOSCA [10].

The superconducting cable. A program has been set up with ECN to investigate the possible use of their powder method Nb_3Sn conductor. As part of this the critical current of a few LHC-type Nb_3Sn cables was measured in the field range 7 to 13 T, results were presented elsewhere [6].

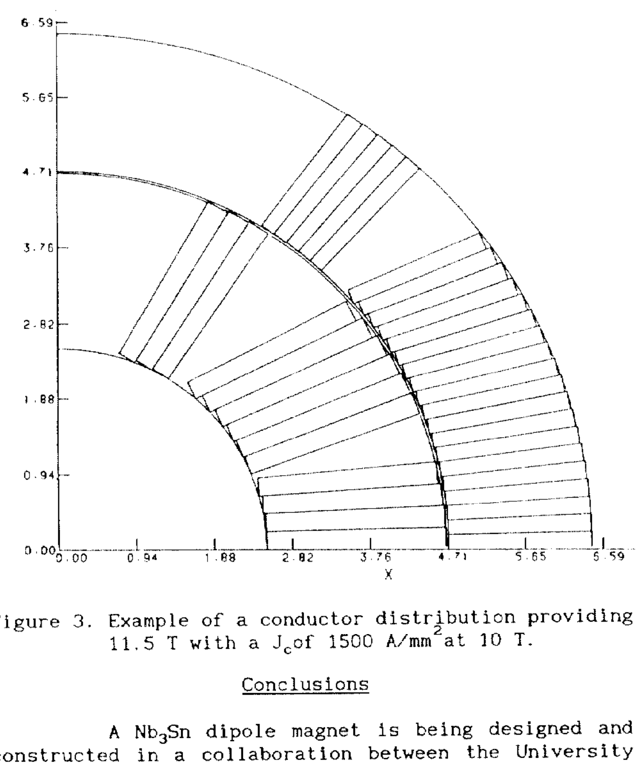

Figure 3. Example of a conductor distribution providing 11.5 T with a J_c of 1500 A/mm^2 at 10 T.

Conclusions

A Nb_3Sn dipole magnet is being designed and constructed in a collaboration between the University of Twente, NIKHEF and CERN. It will be the first 1 meter 10 T Nb_3Sn twin aperture magnet and the second LHC Nb_3Sn dipole magnet.

The proposed application of ECN type of Nb_3Sn wire could lead to the highest possible field in LHC type of dipole magnets due to the superior current density in comparison to NbTi/1.8K or other commercially available Nb_3Sn materials.

The current carrying capacity is sufficient to attain 11 T operation provided the mechanical structure (designed for 11.5 T) and the conductor can handle the enhanced forces. This possibility is the most striking advantage of using this Nb_3Sn conductor instead of NbTi or other Nb_3Sn conductors.

The critical activity is the production of the superconducting cable. A first test of the magnet is scheduled for the end of 1991.

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