# An Experimental 11.5 T $Nb_3Sn$ LHC Type of Dipole Magnet

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***Abstract*- As part of the magnet development program for the LHC an experimental 1 m long 11.5 T single aperture $Nb_3Sn$ dipole magnet has been designed and is now under construction. The design is focused on full utilisation of the high current density in the powder tube $Nb_3Sn$. A new field optimisation has led to a different winding layout and cable sizes as compared to the reference LHC design. Another important feature of the design is the implementation of a shrink fit ring collar system. An extensive study of the critical current of the $Nb_3Sn$ cables as a function of the transverse stress on the cables shows a permanent degradation by the cabling process of about 20 %, still leaving a safety margin at the operation field of 11.5 T of 15 %. A revised glass/mica glass insulation system is applied which improves the thermal conductivity of the windings as well as the impregnation pro-cess considerably. This paper describes various design and production details of the magnet system as well as component tests.**

## I Introduction

The various model magnets built for the LHC as well as SSC during the last years have demonstrated that a magnetic field in the bore in the main dipoles of about 10 T at 1.8 K can just be attained [1],[2]. With the critical current density of the NbTi conductors available today and the two shell cosine (θ) design, this seems to be the ultimate limit. Exploration of higher fields can provide valuable information about the basic limitations and improvements of conductor design, mechanical support system and magnet production. Only with $Nb_3Sn$ conductors is the field range exceeding 10 T accessible. At present $Nb_3Sn$ conductors with non copper $J_c$ of 2000-2500 A/mm$^2$ at 10 T and 4.2 K have become available in industry with which fields of 13 to 15 T appear within reach during the coming years. The effective filament diameter of 20-40 μm in these conductors is still to large to be competitive with NbTi for application in accelerator magnets. Therefore the research is primarily focused on the mechanical problems in the windings to improve the force handling to avoid premature quenching and training.

In the framework of the LHC magnet development program, an experimental 1 m long, 11.5 T $Nb_3Sn$ dipole magnet has been designed and is under construction in the Netherlands. The principle design is based on the high performing ECN type of powder tube conductor which has a non copper $J_c$ of 2000 A/mm$^2$ at 10 T. At the start of the project this conductor was the $J_c$ record holder, while other types of $Nb_3Sn$ conductors showed current densities of 800 to 1400 A/mm$^2$. At this moment also some MJR $Nb_3Sn$ wires have current densities in the 2000-2500 A/mm$^2$ range.

Manuscript received September 20 1993. This research in the program of the Foundation for Fundamental Research on Matter (FOM) has been supported, in part, by the Netherlands Technology Foundation (STW).

These will be used to construct another experimental high field dipole magnet.

Apart from the high target field which will be realised within the geometrical limitations of the LHC design, the aim of this project is to develop alternatives for cable design, mechanical support, conductor insulation and production techniques. The test results of a few twin aperture NbTi model magnets at CERN revealed no specific problems with respect to the common yoke configuration [1]. Therefore the aim of this project has been altered into the realisation of a single aperture magnet.

## II Design Characteristics

### *A. Conductor design*

A general optimisation method for the design of the conductors in dipole magnets has been developed [3]. Apart from geometrical constraints or preferred solutions with respect to the position and tilt angle of the pole plane, the available space, the number of layers, the effective insulation thickness and the cable dimensions, the algorithm also includes the specific $J_c(B)$ relation of the conductor and the required field homogeneity and strength. The starting points are: the ECN $Nb_3Sn$ conductor, a two layer cosine (θ) design, 11.5 T central field, a net insulation thickness of 0.14 mm, a bore of 50 mm and all higher order multipoles $< 10^{-4}$. The iteration process has led to the cable characteristics as summarised in Table 1. Note that these cables are the largest cables ever made for use in an accelerator dipole magnet. In Fig. 1 the results of $I_c$ measurements on original wire and cable samples are presented. In both cases an $I_c$ criterion of 5 μV/m is used. A remarkable degradation due to the cabling is observed, for the inner A cable about

TABLE 1.
CABLE PARAMETERS.

| | Inner cable A | Outer cable B |
|---|---|---|
| Dimensions [mm] | 1.97/2.21x21.8 | 1.73/1.82x17.9 |
| Number of strands [] | 33 | 33 |
| # of filaments [] | 192 | 192 |
| Filament diam. [μm] | 40 | 35 |
| Strand diam. [mm] | 1.26 | 1.00 |
| Twist pitch [mm] | 147 | 146 |
| Filling factor [%] | 85 | 86 |
| Operating current [kA] | 17.7 | 17.7 |
| Max. field in cable [T] | 11.7 | 9.6 |
| Max. eq. stress [MPa] | 140 | 90 |

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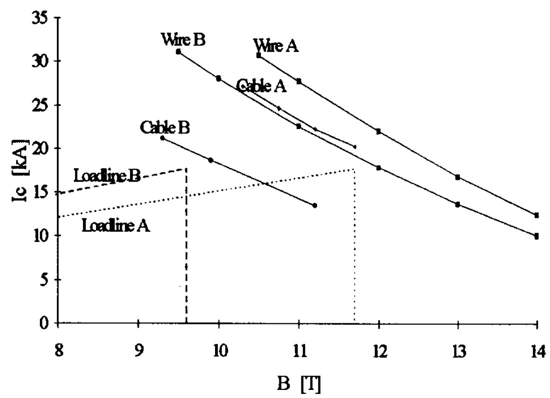


Fig. 1. Ic characteristics of the cables and the original wire material. Wire currents multiplied by the number of strands in the cable. A and B refer to the inner and outer layer respectively.

20 % and for the outer B cable 25 %. The cables were made only once so obviously the cable production parameters are not optimal. Similar cables made of the same conductor did not show this degradation. Nevertheless a safety margin at the operation current of about 15 % for both cables remains. The effect of transverse forces on the Jc of the cables is investigated. A short impregnated sample of the B cable, loaded with a transverse pressure of 150 MPa, which is about equal to the maximum stress in the inner layer in the median plane, shows a reversible degradation of 5-8 % [4]. Incomplete impregnation of a sample or the absence of filler material (e.g. glass fibres) can lead to a much larger degradation of 10-15 % which is only partly reversible. The results show the potential of $Nb_3Sn$ but also the importance of secure and a reliable impregnation of the windings.

*B. Coil supporting system*

Initially a full ANSYS investigation has been performed of a 2-in-1 magnet. The results indicate that a reliable performance of a ring shaped shrink fitted collaring system can be expected [5]. The advantageous properties with respect to a controlled room temperature prestress, the all around coil support and the increased bending stiffness clearly justify the application and practical test in this single aperture magnet. A separate stainless steel pole insert facilitates shrinking the collars around the coil halves and enhances the prestress in the coils. Alignment of the poles of both layers favours the stress distribution inside the coils and is achieved by inserting a copper piece between pole insert and the first winding in the second layer. Compressive stress in the coils at all stages can only be achieved if the Young's modulus of the coils is 15-20 GPa. An additional work hardening step by pressing the impregnated coils to their final dimensions is necessary.

The design principles used in the analysis of the twin aperture magnet are adopted also for the single aperture system. However, the yoke has a vertical split which will stay open during all stages. The demand for a closed gap is too severe a limitation with respect to the purpose of this system, that is to attain the highest possible field with this $Nb_3Sn$ material. The outer stainless steel cylinder is not connected to the end plates. Eight 20 mm thick pulling rods going through holes in the yoke will take care of the adjustable axial support. The interference between yoke and collars is explicitly defined by an arc shaped zone at the inner radius of the yoke plates. The revised mechanical analysis for the single aperture geometry resulted in a supporting system as depicted in Fig. 2. At all surfaces where elements can or will slide, low friction phosphor-bronze sheets covered with MoS powder are introduced. In Table 2 the main parameters of the supporting system are summarised.

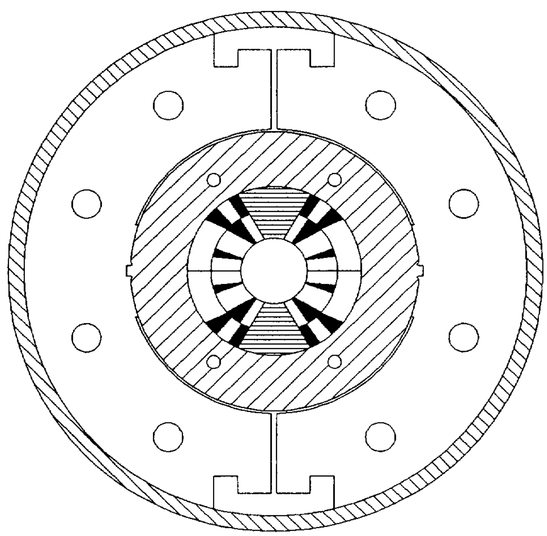

Fig. 2. Cross section of the single aperture magnet showing the coil supporting system.

TABLE 2.
PARAMETERS OF THE MECHANICAL SUPPORTING SYSTEM.

| | | |
|---|---|---|
| Lorentz force x direction | [MN/m] | 6.5 |
| Lorentz force y direction | [MN/m] | 1.6 |
| Lorentz force on coil head | [MN] | 0.9 |
| Max. equivalent stress inner layer | [MPa] | 140 |
| Max. equivalent stress outer layer | [MPa] | 90 |
| Inner diameter coils | [mm] | 50.0 |
| Outer diameter coils | [mm] | 129.9 |
| Outer diameter Al collars | [mm] | 214.0 |
| Outer diameter iron yoke | [mm] | 376.0 |
| Outer diameter ss. cylinder | [mm] | 395.0 |

## III. Coil Production

### A. Coil winding and end spacer design.

The winding of the large inner A cable is a priori the most difficult and tedious job in the production process. After winding and heat treatment of a first dummy coil it appeared, that although the cable is pressed firmly on the winding mandrel, especially near the end pieces, the turns in the first block stay 2 mm distant from the mandrel over a length of 30 mm. This defect is transferred to turns in the following blocks. Although the gaps thus created can be filled, the local support will be degraded. In the turns of the following blocks large deformation from the original cable cross section occurs. Because the successive turns deform in the same way no extra gaps between the turns are introduced, not even after pressing and heat treatment.

Each conductor block is supported in the coil head by its own end spacer. One type consists of a stainless steel filler element that is placed on the mandrel, leaving some space to the block just wound. A stainless steel strip of 1 mm thick, that is hard soldered to a copper wedge, is bent a few mm away from the filler element into its natural shape. This shape appears to be a proper inner support for the next turns. For the other type the smaller space between the strip and last turn is filled with a mixture of castable alumina and sand, that can easily be removed after the heat treatment. Afterwards, all open spaces are filled tightly with fibre glass. These strip end spacers are easy to make, flexible and form continuous paths from the straight section into the coil head, which favours the mechanical support and prevents damage to the cable insulation. In this way a dummy inner and outer layer have been wound and meanwhile the new winding technique using these end spacers is fully developed.. To reduce the effective insulation thickness the coils are pressed to a well defined size with a pressure of about 50 MPa.

### B. Cable insulation

Initially a glass/mica tape had been used for cable insulation, wrapped around the cables with 50 % overlap. This insulation system however results in a very low shear strength and dangerously low thermal conduction in the windings due to insufficient impregnation of the mica layers under pressure [6]. An alternative is to apply a single sheet of the same glass/mica tape parallel with the cable covering one broad side of the cable and both edges. Additionally a wrapping of traditionally woven tape of S2glass without overlap is applied. This wrapping holds the glass/mica tape in position, improves epoxy penetration into the winding package, enhances the shear strength and increases the effective thermal conductivity of the insulation layer by at least a factor 2 at 4.5 K. Fig. 3 shows results of measurements of the heat conductivity of both insulation systems performed on stacks of cables, that are pressed, heat treated and impregnated like real coils.

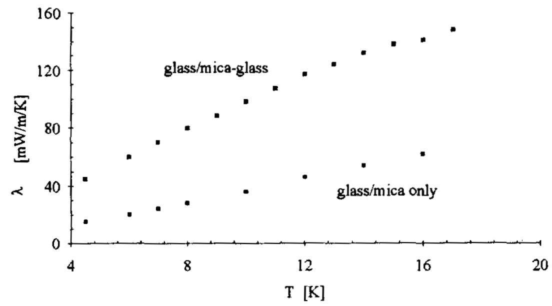


Fig. 3. Experimental data of the effective heat conductivity of the insulation layer between adjacent cables in the coil windings for the old and new cable insulation systems.

The experimental error amounts to about 10 %.

The heat treatment of the wound and pressed coils takes place under vacuum at 680 °C. During this process most of the binder material from the glass/mica tape evaporates at about 300 °C and is deposited at cold surfaces in the oven. The remainder does not cause any problems with respect to electrical insulation or binding of epoxy resin. The glass tape it is heat treated in air at 300 °C before use.

### C. Electrical connection between the coils

The different widths of the inner and outer cables, as well as the complex reaction process, demand a different layout of the joint and the soldering technique than the usual splice. Instead, the first turn of the second layer is placed in the pole plane of the first layer over a length of 3 twist pitches. After both coils have been heat treated separately they are stacked. A connection piece which consists of a copper plate, wrapped with reacted $Nb_3Sn$ wires, is put in place and connects both coil terminals. The connection piece and both coil terminals in both layers are soldered simultaniously with Ag/Sn. A connection produced in this way has a resistance when carrying 20 kA, that ranges from 0.3 nΩ at 0 T to 1.5 nΩ at 10 T. The heat is conducted away to the helium bath by an extension of the copper plate which sticks into the bore and which is mounted after impregnation.

### D. Impregnation of the pole

After soldering, both layers are equipped with a G10 end piece. At this stage temporary pole inserts are installed. The stacked layers are placed upon an impregnation mould and covered by the same precision pieces as used during pressing. Between coils and supporting elements steel foils of 0.05 mm, covered with a non adhesive layer, form the vacuum enclosure. The epoxy resin is the CIBA GEIGY MY740/HY906/DY062 system with a pot life of 6 hours at 55 °C. After impregnation the final stainless steel pole inserts are mounted and eventually they are equipped with shims at the pole faces to adjust for dimensional deviations.

*E. Coil assembly and collaring*

The effective Young's modulus of the impregnated poles is about 2-5 GPa and plastic flow at low pressures occurs. Under this condition sufficient prestress build-up during collaring is impossible. Therefore the 0.5 mm tangential oversized impregnated poles are pressed to their final dimensions, thus entering the elastic region which is characterised by a Young's modulus of at least 18 GPa. Hereafter locally the insulation at the inner radius is removed to enable mounting of voltage taps and thermometers. After installation of the quench heaters two poles are stacked and equipped with mass insulation. Finally two 0.2 mm phosphor-bronze sheets, whose closing lines are placed diametrically to each other, are tightly wrapped around the coils and locked with a soldering connection.

The stacked collar laminates are heated up to 200 °C which creates 0.3 mm radial mounting space for the coils that are inserted into this stack in about 10 seconds. The aluminium collars shrink 0.08 mm into the coils, which provides a prestress of 65 MPa in the coils. The mounting procedure of the yoke and outer shrink cylinder is straightforward.

*F. Sensors in the coils*

The inner layer will be equipped with voltage taps and thermometers. Both can register the quench propagation in the inner layer. For this purpose miniature germanium resistors are used (diameter. 1.6 mm, length 5 mm). They are characterised by a sensitivity of a few kΩ/K with a resistance of 10 kΩ at 4.2 K and a relatively low magnetoresistance of less than 3 % at 8 T [7]. Thermometer and measuring wires are thermally insulated which enables registration of the actual cable temperature during ramping of the magnet current. For registration of the prestress, strain gauge transducers are integrated in the pole inserts of the inner layer coil.

## V. CONCLUSIONS

An 11.5 T single aperture 1 m long dipole magnet has been designed and is under construction. With this magnet the applicability of $Nb_3Sn$ conductors for future high field accelerator dipole magnets generating magnetic fields in the 12 to 15 T range will be investigated. The magnet system is characterised by a new approach with respect to cable dimensions and winding layout, mechanical support with ring shaped shrink fit collars and an improved insulation system. Compared with more traditional insulation systems a combined glass and glass/mica insulation enhances epoxy resin to penetrate the insulation system and the coil package completely and it increases the thermal conductivity in the windings by at least a factor 2 at 4.2 K.

The measured performance of the cables, even under a transverse pressure of 150 MPa, has shown that 11.5 tesla may be attained still leaving a margin in critical current density of 15 % at the operation current of the magnet of 17.7 kA.

A two layer dummy pole has been wound, reacted and impregnated according to the described methods. Winding of the actual $Nb_3Sn$ coils has been started. Completion of the coils is foreseen spring next year, followed by an extensive test program.

The winding experience built up during the production of the NbTi model dipoles and our magnet, as well as the results of the test programs has shown, that the magnet performance mainly depends on the technical ability to produce mechanical sound windings, with the emphasis on the coil heads. Finding and understanding the right combination of cable dimensions, mechanical properties of the cable and the insulation system, appears to be the essential task to make progress. Therefore the cable design has to be dominated by mechanical and technical possibilities and limitations, rather than by electromagnetic considerations.

The tendency is towards the use of smaller cables (at a lower operating current) with more strands (up to 60) which enables production of predictable and better performing coil heads in terms of training behaviour. The presently designed experimental 4 layer 13 T dipole magnet at LBL is an example of this approach [8].

On the other hand, in the case of high field $Nb_3Sn$ magnets the windings are fully impregnated, which implies a quite different mechanical behaviour. The test results of the 11.5 T magnet described here may provide within a few months valuable information for discussion.

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