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FOR LHC BREAK THE 10 Tesla FIELD THRESHOLD

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FIRST Nb_3Sn , 1m LONG SUPERCONDUCTING DIPOLE MODEL MAGNETS FOR LHC BREAK THE 10 Tesla FIELD THRESHOLD

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Abstract

Since late 1986 CERN and ELIN joined in a collaboration to develop a 1 m long, 50 mm aperture Nb_3Sn high field dipole model magnet for LHC. CERN provided the basic know-how and the cables and ELIN was doing design and manufacturing both of a mirror test dipole followed by a final dipole magnet. A winding technology has been developed based on the "wind and react" method. The excitation coils are wound of two different, 17 mm wide, Nb_3Sn cables with an inorganic insulation. After reaction the coils are epoxy vacuum impregnated and mounted into a mechanical support structure consisting of Al-collars, a split cold iron yoke and an outer aluminium cylinder. Design and technology were proved in a magnetic mirror dipole where a single pole was tested in February 1989: a maximum magnetic field of 10.2 T was reached at 17.4 kA and 4.3 K after a few quenches. The dipole magnet itself was successfully tested at the beginning of June 1989: a central bore field of 9.5 T was reached at 4.3K, the maximum field at the Nb_3Sn cable being about 10.05T.

The results achieved represent world record performance for high field dipole configurations and fully confirm the soundness of the chosen technological options. Together with earlier successful testing of NbTi wound model dipoles working at 1.8K, CERN's high field collider magnet development is now solidly based on two very promising technologies. These technologies now are the basis for the development of 10 m long twin-aperture dipoles for the LHC.

Introduction

CERN is studying the implantation of a Large Hadron Collider in the already existing 27 km long LEP tunnel (1). The existence of this tunnel represents a great advantage for the project. Since the attainable beam energy however is directly proportional to the magnetic field of the magnets, it is important to push the technology of superconducting magnets towards the highest possible fields. The envisaged field level is in the 8 to 10T range. About 2000 dipole magnets of the "twin aperture design" will be required, each about 10 m long (1). Currently the development of two magnet technologies is being pursued:

The first line makes use of superconducting NbTi cables for the

excitation coils, cooled by superfluid helium at 1.8K. This solution requires a cryogenic system which is complex in comparison with a liquid helium system working at 4.2K. Following this technology, a 1m long single bore superconducting dipole magnet had been built (2) and successfully tested. A promising central field of 9.3T was obtained.

The second line makes use of Nb_3Sn cables for the excitation coils, the coils being manufactured according to the "wind and react" method (3) and working at about 4.2K. This method is the only one to be envisaged in view of the very small bending radii which are to be realized during winding of the coils.

Technological development was required to solve the problems related to the special insulation which has to withstand the Nb₃Sn reaction temperature of about 700°C. Due to the brittleness of Nb₃Sn, the coils must be vacuum-impregnated after reaction.

General design

Although the dipole is called a model magnet, its transverse dimensions, aperture, coil cross-section, collars and iron structure correspond to future dipole magnets for LHC. The length, however, is reduced to 1m instead of 10 m and also the magnet has only one bore instead of the twin-aperture design envisaged for LHC (4).

Nevertheless the model magnet includes all main "problems" such as the high reaction temperature resistant cable insulation, the determination and shaping

of the coil ends, the necessarily low-ohmic splice connection between the two Nb₃Sn cables and between Nb₃Sn and the outgoing NbTi cables respectively, the tooling and many others.

The dipole cross-section is shown in figures 1 and 2: the inner and the outer layer of the excitation coils are wound with two different Nb₃Sn cables. Collars made of a special aluminium alloy are placed around the coils, surrounded by two vertically split iron halves and finally an outer retaining cylinder also made of a special aluminum alloy with high tensile strength. Figure 2 exhibits the distribution of the insulated cables into current blocks, the blocks separated by key-stoned copper wedges in order to obtain a dipole field with minimum harmonic content.

The mirror cross-section is shown in figure 3. The mirror was designed as a coil test facility. Thus only one coil system is inserted, the other coil system being replaced by a magnetic "mirror" iron insert. Comparing figures 1 and 3 one realizes that the mirror does not use collars, and its outer diameter is reduced.

The main parameters of the magnets, computed for a central field of 10T, are

Central field	10 Tesla
Nominal cooling temperature	4'2 K
Nominal current (dipole)	16'35 kA
Maximum field at inner cable....	appr. 10'5T
Maximum field at outer cable....	appr. 8'8T
Magnetic forces, total	x 4600 kN/m
	y -2400 kN/m
	z 360 kN
Stored energy (dipole)	316 kJ/m
Stored energy (mirror)	177 kJ/m

Mechanical structure

As the electromagnetic forces at 10T are extremely high, a "hybrid" mechanical structure was chosen (4) (7). In such a structure as shown in figure 1, pre-stressing of the coil/collar assembly at room temperature provides only a part of the final coil pre-stress. During the cool-down the coil/collar assembly is further compressed due to the shrinking of the outer aluminum cylinder. This effects the closing of the (carefully computed and checked) vertical gap

Fig.1: Schematic cross-section of the 1m long full aperture dipole magnet

between the split iron halves. Once closed, the compressive forces generated on the gap planes more than counterbalance the outwards directed horizontal electromagnetic forces of the fully energized dipole magnet. This two-way compression of the coils as well as the whole mechanical structure had been verified on a full-cross-section 15cm mechanical model. The finite element computations had been confirmed with fair accuracy (6).

The stresses in the active parts remain within tolerable limits. The distribution of stresses and deformations of the coils had to be optimized in order to minimize the effect of disturbing the field harmonics. The whole structure must be designed in such a way that the coils are kept always and everywhere under compression. In choosing the initial prestress in the Nb₃Sn coils one has to be careful: on the one hand, permanent compression on all parts of the coil is indispensable, on the other hand measurements on Nb₃Sn strands and on

Nb₃Sn cables indicate a decrease of the critical current under transverse compression (5). Thus the total coil stress at 4.2K has to be chosen very carefully i.e. between the minimum tolerable compression of the coils at the most critical interface with their center posts and the maximum tolerable compression on the midplane between the coils (6).

The Nb₃Sn cables

The dimensions of the two tapered Rutherford-type cables for the inner and for the outer layer are: 2'19/2'69 x 16'81 mm² for the inner layer and 1'47/1'79 x 16'81 mm² for the outer layer, respectively. The cables are insulated, 0'14 mm each side. The thicker cable consists of 24 strands of 1'38mm diameter with 50 000 Nb₃Sn filaments of 2'56µm in a bronze matrix; the Cu/non-Cu ratio is 0'38; a cross-section of the cable is shown in reference (6). The thin cable consists of 36 strands of 0'92mm diameter with 20 000 Nb₃Sn

Fig.2: Cross-section model of collared coils

Fig.3: Schematic cross-section of the mirror dipole

filaments of $2.56\mu\text{m}$ each; here the stabilizing Cu/non-Cu ratio is 0.36. For the mirror, the inner cable had the same overall dimensions as the thick cable mentioned above, but with a reduced Cu/non-Cu ratio of 0.22 and thus a higher content of Nb₃Sn. All cables were delivered by Vacuumschmelze GbmH (Germany). Details concerning these cables and their successful testing were exposed in reference (6). The cable performances as well as the calculated load lines are summarized in figure 4.

Magnet manufacturing

The various coil layers are wound with insulated (but non-reacted) Nb₃Sn cables on an appropriate winding machine. The machine is equipped with precisely machined mandrels, clamps and compression devices in order to ensure a correct geometry of the coils. The wound layers

Fig.4: Cable I_c -lines and calculated coil load lines

are placed into a reaction oven to be reacted "in situ" in inert gas. The reaction temperature was 675°C and the duration 144 hours. As the coils are fabricated according to the "wind and react" process, only glass and/or mica tapes could be used for the interturn insulation. Preceding detailed investigations concerned the performance of the insulation: reasonable mechanical strength both before and after thermal treatment, dimensions under compression, good impregnability, sufficient dielectric strength, etc.

After reaction, the internal coil splice between inner and outer layer is done. This Nb₃Sn-Nb₃Sn junction was specially developed in order to achieve a low-ohmic connection with ≤ 1 Nanoohm at $17.4\text{ kA}/10\text{T}/4.2\text{K}$.

Each excitation coil, composed of one inner layer and one outer layer, is then covered by a coil-to-ground insulation. After brazing the Nb₃Sn-NbTi junction of the outgoing cables the coil is placed into a precisely machined impregnation mould, pre-tested and vacuum impregnated with epoxy resin.

A high standard of quality assurance is indispensable during coil fabrication; corrections after the vacuum impregnation are absolutely impossible.

After impregnation, the coils are pre-compressed and the elastic modulus is determined. After assembly of coils and collars the collars are compressed and locked. As the magnetic forces are high when the magnet is energized, rigid collars and appropriate clamping of the collars is indispensable. Different collar designs and clamping methods were investigated and experimentally proven. All tests were performed at room temperature as well as in liquid nitrogen (6).

The collared coil pair is placed into the laminated iron halves and the rigid end plates for the retention of the axial forces are tightened by strong longitudinal bolts. Finally the outer cylinder made of aluminium alloy is shrink fitted, the two coils are interconnected and the outgoing cables tightly fixed into their support structure. Instrumentation wiring is done followed by final inspections and tests.

Results of mirror tests and main dipole tests

The 1m long, 5cm-half-bore mirror dipole (cross section see figure 3) was tested at CERN in February 1989. Several test runs were made, varying both the current ramp rates and the operating temperature and also included thermal cycles. The quench history is shown in figure 5: After a few quenches, a maximum field of 10.2T was attained at 4.3K with an excitation current of 17.43kA. When cooled to 1.8K, the quenches were registered at essentially the same field which means that the mechanical limit of the mirror was reached. After one full thermal cycle the mirror magnet again reached the same field level mentioned above without re-training.

The 1m long, 5cm-full-bore main dipole (cross section see figure 1) was tested at the beginning of June 1989 at CERN. Figure 6 shows the magnet, being prepared for testing. This magnet reached a central bore field of 9.5T at 4.3K, which is related to a maximum field at the innermost turn of the inner layer of about 10.05T. Thermal cycling of the

magnet did not affect the field level, too; that means that practically no retraining occurred.

The field level obtained in the mirror is slightly higher than in the main dipole. This is due to the fact that the inner mirror cable contains more Nb₃Sn than the inner cable of the main dipole. Additionally the magnetic forces and thus stress effects in the main dipole are higher than in the mirror.

Conclusion and prospects

The successful development, fabrication and testing of the mirror device as well as of the 1m long, 5cm aperture main dipole magnet fully confirmed the validity of the technological options of Nb₃Sn and of the "wind and react" technology. Both magnets were designed and manufactured in an industrial style and reached record field levels. To achieve this outstanding results, the ELIN-CERN collaboration was pursuing a vigorous technological effort related to all crucial components of the magnets. Also the considerable potentials of superconducting Nb₃Sn cables for high fields and high currents were confirmed.

Fig.5: Quench history of the mirror dipole and of the main dipole

Fig.6: 1 m dipole magnet at the cryo-lab at CERN.

However, a continuous effort should follow this great initial success. It should aim at the development of advanced and/or less expensive Nb₃Sn cables and the development of better inorganic insulation materials, which would lead to a safer and quicker coil fabrication and thus reduce fabrication costs. Another concentrated effort is requested to clarify the effect of transverse compression on the critical current of Nb₃Sn cables in the presence of high magnetic field, this effort being necessary to exploit the possible design limits of Nb₃Sn magnets.

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