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FIRST RESULTS OF THE HIGH-FIELD MAGNET DEVELOPMENT
FOR THE LARGE HADRON COLLIDER

The CERN LHC Magnet Team, reported by R. Perin

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ABSTRACT

After a review of the present state of the R.&D. programme, the results of the tests of the first three model magnets are described.

The first magnet, designed and built as a joint venture by CERN and ANSALDO Componenti, Italy, is based on the NbTi technology. It was designed for 8 T nominal field, but it passed 8.5 T without any quench and attained a 9.3 T central field. Three test campaigns were performed, two at CERN and one at the CEA, Saclay, Laboratory (France). No re-training occurred even after having kept the magnet at room temperature for several months. A second magnet of the same design, but using a mechanically stronger conductor insulation, showed good reproducibility of results and reached a 9.45 T central field at 1.8 K.

The third magnet, based on the Nb₃Sn wind-and-react technology, was a joint project of CERN and ELIN-UNION, Austria. Design and technology were at first tested in a magnetic mirror device in which a full magnet pole was tested : 10.2 T central field was reached after a few quenches. The complete magnet was tested in June 1989 and reached a 9.5 T central field at 4.3 K.

INTRODUCTION

A high-energy proton-proton collider is proposed at CERN as the next facility to push further the frontiers of particle physics. This Large Hadron Collider (LHC) [1] would be installed in the tunnel of the Large Electron Positron Collider (LEP) which is now completed. The envisaged field level in the dipoles is in the range 8 to 10 T. To prepare for the LHC, an R.&D. programme has been launched for both presently possible routes to high-field magnets, i.e. using NbTi superconductor at about 2 K and Nb₃Sn at 4.5 K [2].

A Collaboration has been set up by CERN and several European Laboratories and Institutions [2]. Some co-operation

agreements have been officially established as shown in Table 1, while the other Institutions are collaborating, still in an informal way.

Industry is taking part in the R.&D. effort, not only in the development of components, but also in the design and construction of magnet models and prototypes. The most important common development projects with industrial firms are listed in Table 2. Other collaborations concern development of superconducting wires and cables, insulation systems and cryostat design.

The first magnet model (8TM1) has been designed and built as a joint venture of CERN and the firm ANSALDO Componenti, Italy [3]. A second model magnet (8TM2) of the same design was built by the same firm. A third magnet

TABLE 1

OFFICIAL CO-OPERATION AGREEMENTS WITH EUROPEAN INSTITUTIONS

Institute	Subject of common development
CEA (France)	<ul style="list-style-type: none"> -- Test station for dipole magnets -- 1.8 K helium circulation test installation -- Measurements of properties of cables -- Heat transfer studies -- Design and construction of a prototype quadrupole
INFN (Italy)	<ul style="list-style-type: none"> -- Development of NbTi conductors with 5 μm $\emptyset$ filaments -- Construction of 10 T, twin-aperture, magnets
FOM-UT-NIKHEF (Netherlands)	-- Development of a 10 T twin-aperture dipole model magnet with Nb ₃ Sn conductor

model, using Nb₃Sn superconductor was designed and built [4,5] as a joint project of CERN and ELIN-UNION, Austria.

The single aperture configuration has been adopted in this initial development phase in order to limit investment on tooling and conductors, and the design field of the first two models was limited at 8 T because at that time cables with the width needed for a 10 T design (~ 17 mm) were not available. In the meantime 17 mm wide cables with the appropriate aspect (width/thickness) ratio were developed by European industry and a 10 T, twin-aperture, NbTi magnet was designed [6,7] (Fig. 1). Four 1 m long model magnets are being built by Ansaldo (I), Elin (A), Holec (NL) and Jeumont-Schneider (F).

To further explore the Nb₃Sn route, the development of a 10 T twin-aperture model magnet has been started in the Netherlands by a CERN-FOM-UT-NIKHEF Collaboration [8].

In parallel with the short model magnets, a 9 m long twin-aperture prototype [9] was designed at CERN and ordered to ABB, Germany. It uses HERA type coils in order to save time and money, but the rest of the structure corresponds to the LHC 10 T design. The cryostat is being made by FBM, Italy. The complete cryomagnet will be tested in CEA, Saclay, France, in spring 1990.

Design of a full size (~ 10 m long) 10 T, twin-aperture prototype dipole has been started in collaboration with INFN, Italy, and procurement of the necessary conductor and major tooling has been initiated.

FIG. 1 Cross-section of the LHC 10 T magnet

RESULTS OF CABLE DEVELOPMENT

The cable for the inner layer, made of 26, 1.29 mm $\emptyset$, strands has the overall dimensions 2.06/2.50x17mm². The cable for the outer layer made of 40, 0.8 mm $\emptyset$ strands, has 1.3/1.67x17 mm² cross-section. The mechanical stability of these unsoldered cables is now acceptable for winding. The current densities obtained in the outer cable are suitable for LHC : 1100 A/mm² in the NbTi at 8 T, 4.2 K in 15 μm filaments. The fabrication process is now being optimized to obtain high current densities in strands of 1.29 mm $\emptyset$ with 5 μm NbTi filaments.

TABLE 2

COMMON DEVELOPMENTS WITH INDUSTRIAL FIRMS

<u>FIRM</u>	<u>Subject of common development</u>	<u>Starting year</u>	<u>State</u>
ANSALDO Componenti (Italy)	Design and manufacture of a 1 m long, 8 T, NbTi model dipole (8TM1)	1986	Successfully concluded
ELIN-UNION (Austria)	Design and manufacture of a 1 m long, 9 ÷ 10 T, Nb ₃ Sn model dipole	1986	Successfully concluded
TESLA ENGINEERING assisted by RAL (U.K.)	Design and manufacture of a prototype sextupole/dipole corrector	1988	In progress
ABB (Switzerland)	High current diodes for magnet protection	1988	In progress
ACICA Consortium* (Spain)	Design and manufacture of a prototype tuning quadrupole	1989	In progress

*) ACICA includes the following firms : ABENGOA, AME, CANZLER, GENEMESA and INDAR.

For Nb₃Sn, current densities of 1600 A/mm² at 11 T, 4.2 K, in the non-Cu part have been obtained in 15 to 20 µm filaments following the powder method [10].

TEST STATIONS

CERN

The 1 m long (1.35 m overall length) models have been tested in the CERN 1.8 K test station. It mainly consists of a vertical double-bath cryostat, a 100 l/h refrigerator/liquefier, a 20 kA power supply and suitable cryogenic current leads. Bath temperature can be varied between 4.2 K and 1.6 K. Cooling capacity at 1.8 K is approximately 10 W [11].

CEN-SACLAY

A larger installation [12] has been built at CEN-SACLAY for testing model and prototype (10 m long) magnets for the LHC. The cooling power of the liquifier for the test of the first model (8TM1) was 200 W at 4.4 K. For the tests of the prototypes the cooling power is being increased to 450 W at 4.4 K and to ~ 40 W at 1.8 K.

8 TESLA MODEL MAGNETS

8TM1

This magnet model is an 8 T nominal field, single-aperture, 50 mm bore, 1 m long dipole using NbTi conductor and operating at superfluid helium temperatures. In its design [3,13] care has been taken to choose components that could be easily procured. So, the superconducting cable was designed such that use could be made of strands left over from the production of the cable for the DESY-HERA project [14]. The magnet cross-section is presented in Fig. 2 and the assembled magnet in its helium container is shown in Fig. 3. A list of the main parameters is presented in Table 3. The superconducting cable, supplied by Vacuumschmelze GmbH (Germany), is impregnated with a $3.5 \times 10^{-8} \Omega\text{m}$ (at 4.2 K) resistivity solder.

The design of the force containment structure was made for a 9.5 T central field. The coils are surrounded by 3 mm thick laminated aluminium alloy collars which are locked together by longitudinal stainless steel tie rods. The iron yoke is vertically split in two symmetric parts which are mounted around the collars under a pre-determined horizontal compressive force and with a

~ 0.5 mm vertical gap between them at room temperature. They are clamped by a stainless steel shrinking cylinder which pushes the iron halves to close their gap during cool-down. The functioning of this special mechanical structure, first proposed in 1985, has been described elsewhere [13]. Half of the axial e.m. force (~ 200 kN at $B_0 = 9.3$ T) acting on the magnet ends is supported by thick stainless steel plates that are fixed to the shrinking cylinder.

Two test campaigns took place at CERN. In the first one the central field was voluntarily limited at 9.1 T. The magnet was subsequently warmed up to room temperature and then cooled down again for the second campaign of tests. A third test campaign was carried out at CEN, SACLAY, France, [15] in a horizontal cryostat after the magnet had stayed at room temperature during six months. The shrinking cylinder of the magnet formed the main part of the helium container in the horizontal cryostat (Fig. 3). The history of quenches can be seen in Fig. 4. The first quench occurred at 8.55 T central field. At the second cool-down 9.3 T were reached at the third quench. After the third cool-down two natural quenches occurred, the first one at 8.9 T and the second at ~ 9.35 T (10530 A) showing an excellent behaviour of the magnet after a half year at room temperature.

FIG. 2 Cross-section of the 8 T Model Magnet for the LHC

TABLE 3

MAIN PARAMETERS OF 8TM1 MODEL MAGNET

Coil inner diameter	50.0 mm
Coil outer diameter	102.6 mm
Yoke inner diameter	176.8 mm
Yoke outer diameter	396.0 mm
Shrinking cylinder outer Ø	412.0 mm
Coil straight length (inner)	800.0 mm
Overall coil length (outer)	1'060.0 mm
Length (without conn.)	1'265.0 mm
Overall magnet length	1'353.0 mm
Nominal induction B_0	8.0 T
Peak field in winding at B_0	8.3 T
Operation current at B_0	9'180 A
Turns per pole inner/outer	
shell	21/21
Stored energy at B_0	160 kJ
Stored energy at $B_0 = 9.3$ T	216 kJ
Cable geometry	1.31, 1.66 x 12.6 mm ²
No of strands	30
Strand diameter	0.84 mm
NbTi filament diameter	10 µm
Cu/Sc ratio	1.8
Insulation :	
2 x 0.025 mm Kapton 50 % overlapped	
+ 0.12 mm glass fiber, B-stage epoxy	
helicoidally wound with 2 mm spacing	

Artificial quenches have then been initiated by a heater placed on the end of the coil outer layer, delaying the time of opening the power supply switch. With a delay of 96 ms, the maximum temperature in the coil was 107 K. The measured magnetic length was 951.5 mm at 9180 A, to be compared to the coil inner layer straight part of 800 mm.

8TM2

The 8TM2 model magnet is of the same design and has been built by the same manufacturer as the 8TM1. It had two purposes :

- to test a new cable insulation.
- To test reproducibility.

A weak point found in the fabrication of the windings of 8MT1 was the fragility of the cable insulation which led to frequent ruptures at the end bends. A new insulation was developed in collaboration with Isovolta (Austria) replacing the outer glass fiber tape by a new glass aramid fiber tape which was then applied to the conductor by the firm Alfacavi-Pirelli (Italy) (Fig. 5).

FIG. 3 8TM1 Magnet in its Helium Container

FIG. 4 Quench history of 8TM1

The magnet was tested in July 1989. It fulfilled the two above mentioned goals and behaved in a very similar way to 8TM1 reaching a slightly higher maximum central field, 9.45 T at 10660 A.

FIG. 5 Cable insulation for 8TM2 magnet

Nb₃Sn MODEL DIPOLE

The work carried out by the CERN-ELIN Collaboration on a Nb₃Sn model magnet and its results are reported at this Conference in another paper [5]. The complete magnet was preceded by a single full size coil which was tested in a magnetic mirror device. Only the main parameters, Table 4, and results are recalled here.

The 1 m long, 5 cm half-bore mirror dipole was tested at CERN in February 1989. After a few quenches, a 10.2 T maximum field was attained at 4.3 K with an excitation current of 17.43 kA.

The 1 m long, 5 cm full-bore dipole was tested in June 1989 at CERN. It

reached a central bore field of 9.5 T at 4.3 K, which corresponds to about 10.05 T peak field at the conductor.

TABLE 4

MAIN PARAMETERS OF DIPOLE MAGNET
AND MIRROR DEVICE

Central field	10 tesla
Nominal cooling temperature	4.2 K
Nominal current (dipole)	16.35 kA
Max. field at inner cable	appr. 10.5 T
Max. field at outer cable	appr. 8.8 T
Stored energy (dipole)	316 kJ/m
Stored energy (mirror)	177 kJ/m

CONCLUSIONS

Encouraging results have been obtained in the first phase of develop-

ment of high-field magnets for the LHC. The work must proceed with the construction and testing of long dipoles, quadrupoles, correction magnets and auxiliary equipment, in order to establish a sound technological basis for the construction of the LHC.

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