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DESIGN, FABRICATION VARIANTS AND RESULTS OF LHC TWIN-APERTURE MODELS

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Design, fabrication variants and results of LHC twin-aperture models

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Abstract **- In the framework of the R&D programme for the development of high-field superconducting magnets suitable for LHC, four twin-aperture, 1 m long, dipole models have been contracted to industry.**

The magnets are working at superfluid helium temperature below 2 K. The value of the maximum central magnetic field at the short sample limit is 10 T. The main design characteristics and principles of construction are recalled. The four models have technical variants which are described. Superconducting cables of 17 mm width have been developed in collaboration with industry. The measured critical current densities on cables and results of magnet tests are reported.

I. INTRODUCTION

In the frame of the R&D programme for a future Large Hadron Collider (LHC) at CERN, four models of twin-aperture dipoles have been contracted to industry. These models have a length of 1 m. The four companies which have been selected after a call for tender are: Ansaldo (I), Elin (A), Jeumont-Schneider (F), Holec (NL). The reference documents for the construction of the models were a CERN technical specification and the CERN reports of design and calculations. The companies have developed the specific tooling, the detailed design drawings and the protocols of construction and the quality assurance programme. During the design phase, various technical approaches and variants have been studied and implemented in a close collaboration with CERN in order to better qualify the construction in view of the future manufacturing of 1800 twin-aperture dipoles ~ 10 m long for LHC. The contracts were signed in September 1988 and the first two models were achieved in December 1990.

The superconducting cables were ordered by CERN from four suppliers: Alsthom-Intermagnetics (F), ABB (CH), LMI (I), Vacuumschmelze (D) and supplied to the magnet manufacturers. This report describes the functions and the technical variants of the models, the results of the measurements of the cables and the first test results of the models. The technical details of constructions can be found in refs [1, 2, 3].

II. BASIC DESIGN OF THE TWIN-APERTURE MODELS (MTA1)

Fig. 1 shows the cross-section of the twin-aperture magnet. The coils consist of two layers, each with a different high aspect ratio cable made of NbTi composites. The inner layer is subdivided into four blocks of conductors, the outer layer into two blocks to obtain a good field homogeneity. The longitudinal spacers are made of copper. The upper spacer of the inner layer has holes to provide the helium passage to the fish bones located between the two layers. The electrical insulation consists of 25 µm Kapton™ layer (50% overlap) and a B-stage preimpregnated fibre-glass layer spaced by 2 mm. The four poles are assembled in common collars in which they are prestressed at room temperature with an azimuthal prestress of 50 N/mm^2. The iron yoke surrounding the twin collared coils is split into two parts at the vertical symmetry plane of the magnet. The two iron inserts between collars and yoke serve to reduce the quadrupolar component in the twin-aperture dipole. Indeed, the two dipoles being excited in opposite direction, the flux pattern in the yoke exhibits a quadrupolar distribution. The separation line of the flux is at ~ 60°, position which varies with the field level, and not at 90° as in a single dipole. The iron thickness can then be reduced to 8 cm in the horizontal plane compared to 13 cm for a single aperture dipole. Between collars and iron yoke, sliding shims are provided to accommodate the height and the width of the collared coils to the dimensions of the yoke and have a better control of the gap between the two half yokes. When the iron yokes are assembled and compressed on the collars, clamps are introduced and fix the structure at the required force.

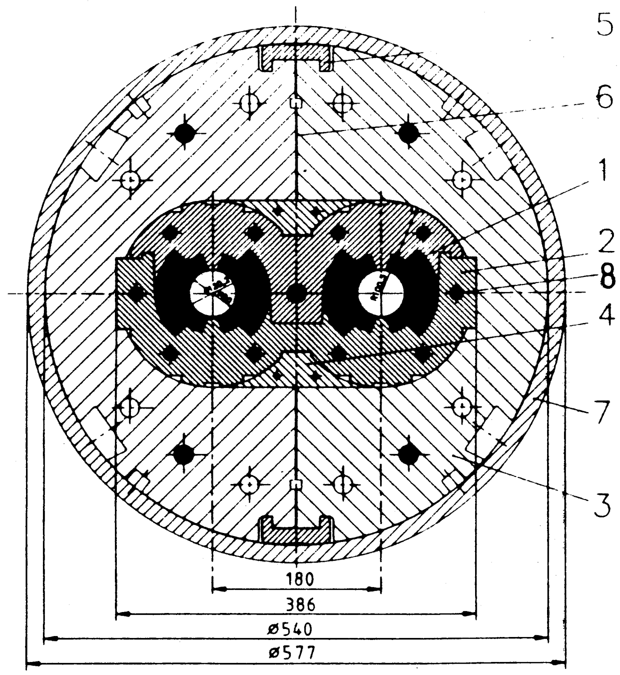

Fig. 1 Cross-section of a twin-aperture dipole
1 Coils, 2 Collars, 3 Yoke, 4 Iron insert, 5 Clamp, 6 Gap, 7 Outer shrinking cylinder, 8 Rods.

TABLE 1
DIPOLE PARAMETERS AT 2 K

Nominal field B_0 (2 K)		10	T
Operation current		14800	A
Coil inner diameter		50	mm
Coil outer diameter		120.2	mm
Distance between aperture		180	mm
Collars outer horizontal dimension		380	mm
Iron outer diameter		540	mm
Stor. energy for both channels combined		684	kJ/m
Self-inductance per single dipole		3.134	µH/m
Mutual inductance	at 1.4 T	7.08	µH/m
between dipoles	at 10 T	153.4	µH/m
Resultant of e.m. forces in the first coil quadrant			
ΣF_x		= 227.6	t/m
ΣF_y	1st layer	= - 23.4	t/m
ΣF_y	2nd layer	= - 98.0	t/m

Around the yoke is a stainless steel or aluminium alloy shrinking cylinder with a prestress at room temperature so that after cooldown the collars and the yoke are in close contact in the horizontal plane and a compression is produced on the mating faces of the yoke parts. The resulting mechanical structure should be very rigid to have small displacements under the large magnetic forces. The two functions (closed iron gap and close contact collars/yoke) depend on the relative dimensions and the relative displacements of the components of the mechanical structure, the choice of the materials, the friction coefficients, the geometrical accuracy and the prestresses at room temperature. The stresses and the displacements in the various conditions are described in refs [4, 5, 6]. The collars and the yoke are in contact only on the horizontal and vertical axis of the structure, elsewhere a clearance of 0.5 mm has been provided. Anti-friction sheets have been provided between all the parts having relative displacements.

The axial forces of 700 kN at 10 T for the two magnets are sustained by the outer cylinder via a 55 mm thick common end plate made of stainless steel. This end plate has a deformation of ~ 1 mm at 700 kN.

The parameters of the twin-aperture model are reported in Table 1.

III. EFFECTS OF THE VARIOUS PARAMETERS OF THE MECHANICAL STRUCTURE

A. *Collar material and prestress at room temperature*

In the four models, the collars are made of aluminium alloy material. Because it is not proven that the stresses in the coils increase by ~ 10 N/mm^2 at cooldown, the average azimuthal compressive prestress on the coils at room temperature has been fixed at 50 N/mm^2, minimum calculated value required for the inner layer before excitation. In the collars, the highest stresses occur near the rods in the horizontal plane at room temperature to sustain the total force of 3400 N/mm for the lateral rods and 6800 N/mm for the central rod. The aluminium alloys used are 5083 G35 and 2014 T6. In some models the rods, which require a higher prestress on the coils for their insertion during collaring, have been replaced by keys.

B. *Support of the iron at the vertical axis and support of collars in the horizontal plane*

Table 2 gives a summary of the effects mentioned when the magnet is excited at 11.3 T.

From Table 2, it can be seen that the collars alone can sustain the magnetic forces but the deformation and the compressive stresses in the coils increase considerably. When the iron is supported at the vertical axis, the magnetic forces are supported equally by the collars and the iron/shrinking cylinder structure. In a first attempt, it has been decided for the four models to reach a small overall deformation of the magnet and lower compressive stresses in the coils at full field by having the yoke halves supported in the vertical plane. The vertical force at the iron support varies from 200 N/mm to 1300 N/mm between cooldown and full excitation of the magnet. At room temperature, a clearance of 0.15 mm between iron and collars at the vertical axis is foreseen for an easier assembly.

C. *Iron gap and outer cylinder material*

At cooldown, the C-shape half yokes undergo a vertical deflection. The mating faces are machined such as to produce a wedge shape gap at room temperature, the two faces become parallel and in contact on their whole surface at cooldown. If the outer cylinder is made of stainless steel, the horizontal displacement of the cylinder/yoke is lower than that of

TABLE 2

Collars supported in horizontal plane	NO	YES	YES
Iron supported in vertical plane	NO	NO	YES
Force on mating faces of the yoke	0	2 x 758 N/mm (26%)	2 x 1349 N/mm (46%)
Force taken by collars	2 x 2924 N/mm	2 x 2166 N/mm (74%)	2 x 1575 N/mm (54%)
Horizontal deformation of collars	0.29 mm	0.17 mm	0.08 mm
Maximum stress on coils	- 180 N/mm^2	- 150 N/mm^2	- 130 N/mm^2
Increase of outer coil diameter	0.36 mm	0.25 mm	0.15 mm

the collars. A prestress force of 3000 N/mm is therefore established at assembly in the outer cylinder which compresses the collars horizontally by at least 0.16 mm. When the iron gap is closed after cooldown, this force is transferred to the mating face of the two half yokes so that the tensile prestress seen by the 10 mm stainless steel outer cylinder stays around 150 N/mm^2. With the outer cylinder made of aluminium alloy, the horizontal force varies from 1000 N/mm at room temperature to 3000 N/mm after cooldown.

III. SUPERCONDUCTING CABLES

The inner layer cable is made of 26 NbTi composites of 1.29 mm diameter. The dimensions of the trapezoidal Rutherford type cable are 2.04/2.50 x 17 mm^2. The outer cable consists of 40 strands of 0.84 mm diameter and has the dimensions 1.3/1.67 x 17 mm^2. The electrical characteristics have been measured on strands taken from the finished cable. The degradation due to cabling does not exceed 5%. The NbTi filament size varies from 10 to 19 μm according to the suppliers. The Cu/Sc ratio is higher than specified. It ranges between 1.75 and 1.90 for the inner cable instead of 1.6, and between 1.8 and 1.96 instead of 1.8 for the outer cable. This explains why the theoretical quenching field varies in the different models. Table 3 shows the current densities obtained at various temperatures after cabling.

TABLE 3

Strand dimension	B(T)	2 K	1.9 K	1.8 K	
0.84 mm Ø	9 T	2230	2300	2360	A/mm^2
	8 T	2790	2830	2900	A/mm^2
1.29 mm Ø	11 T	980	1030	1080	A/mm^2
	10 T	1490	1530	1570	A/mm^2

From these measurements performed at CEA, Saclay, crude relations for the effect of temperature on the current densities are J_c (5 T, 4.2 K) = J_c (8 T, 2 K) and J_c (8 T, 4.2 K) = J_c (10.8 T, 2 K). At high field, the shift in field is 2.8 T when the temperature is reduced from 4.2 K to 2 K.

IV. TECHNICAL VARIANTS IN THE FOUR MODEL CONSTRUCTIONS

Table 4 indicated the technical variants introduced in the four models in collaboration with the suppliers. The ideas were to find solutions more practicable for long magnets and to know their effect on the performances of the magnets. The technical variants concern the type of cable, the electrical insulation, details of the coils, the material, shape and assembly method of the collars, the material of the outer cylinder. The superconducting cables and the iron laminations were supplied by CERN. More details on the construction are given in refs [1, 2, 3].

TABLE 4

Model / Subjects	A	E	JS	H
Cables				
Inner layer	Soldered (Als.)	Unsoldered (Vac.)	Soldered (Als.)	Unsoldered (Vac.)
Outer layer	Soldered (LMI)	Soldered (LMI)	Partially soldered (Als.)	Unsoldered (Vac.)
Elec. insulation				
22% B-stage	Glass-fiber cloth	Glass-Kevlar™ cloth	Glass-fiber ribbon	Glass-fiber cloth
Coils				
End spacers	G11	Bronze	G11	G11
Collars Material	Al 2014	Al 5083 G35	Al 2014	Al 5083 G35
Shape	Common collars	Split collars, separate st. steel pole pieces	Common collars	Common collars
Assembly	Central rod, 2 lateral rods	Lateral keys	1 central rod, 4 lateral keys	Central rod, 2 lateral rods
Yoke				
Nomex in lam.	NO	NO	YES	NO
Yoke assembly	1 m long	1 m long	Separate 30 cm blocks	1 m long
Outer cylinder				
Material	316LN	Al 5083	Al 5083	Al 5083
Assembly	Lateral welds	Warm shrink fitting	Warm shrink fitting	Warm shrink fitting
Max. quenching field at 2 K	9.8 T	9.8 T	10.1 T	10.0 T
Supplier	Ansaldo (I)	Elin (A)	Jeumont-Schneider (F)	Holec (NL)

Only a few general comments are made in this report. The winding of coils with a 17 mm wide cable has been made successfully in industry. The conductor positioning in the ends can be realized with a precision of ± 0.5 mm and ± 1° angle. The electrical insulation was a bit weak and a few electrical shorts appeared, mainly in the transition between the straight part and the ends of the coils. In the straight part, the cable insulation sustained 120 V interturn under a pressure of 100 N/mm^2. The curing pressure to obtain the right dimensions of the coils was ~ 60 N/mm^2. The Young's modulus of the coils is around 15000 N/mm^2.

The collaring of the twin-aperture dipole with common collars was feasible using a two-step operation: firstly, inserting the lateral rods, and in a second step the central rod. The relaxation of the aluminium collars after the press removal could be reduced by partially pulling on the sides of the collars before pushing the collars in the vertical axis of the coils.

The laminations had to be machined from existing stamped laminations used for another project. Due to the deformations of these laminations, the wanted accuracy has not been obtained: they are within a tolerance of 0.1 mm.

The outer cylinders made of aluminium alloy have been assembled with a prestress of 40 N/mm^2.

V. RESULTS OF THE MEASUREMENTS

Three magnets have been delivered by Elin, Jeumont-Schneider, and Ansaldo to CERN. The fourth magnet will be delivered in the near future. The measurements are performed in a vertical cryostat [7]. The field and its harmonic content are analysed.

The three magnets exhibit a similar training behaviour starting at 8 T before reaching in 7 quenches a maximum field of 9.05 T at 2 K; this value corresponds to 92% on the load line of the short sample limit. At 4.2 K, the magnets reached their short sample limit of 7.9 T.

The training behaviour of the three magnets is reported in Table 5.

The tests and detailed analysis of the magnet behaviour are not yet completed.

The voltage recording at a quench indicates a large voltage difference between the two dipoles of the twin aperture and no voltage difference across the single dipoles.

The majority of quenches appear on one dipole of the twin-aperture dipole. More tests and analysis are necessary to understand the similar magnet behaviour in the three magnets and investigate the origin of quenches.

TABLE 5

	E	JS	A
B after 5 quenches	8.8 T	8.75 T	8.4 T
B_{MAX} at 2 K	9.05 T	8.9 T	8.6 T
B_{MAX} at 4.2 K	7.9 T	7.6 T	7.9 T

VI. CONCLUSIONS

Twin-aperture models have been built in industry. These magnets which are very compact are the first twin-aperture magnets tested in the framework of the R&D programme for LHC. The envisaged field level for LHC is in the range of 8 to 10 T at 2 K. The twin-aperture magnets attained the short sample limit at 4.2 K, but do not reach the short sample limit at 2 K and exhibit training. A programme for understanding the training behaviour is under way at CERN.

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