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STRUCTURAL ANALYSIS OF THE LHC 10 T TWIN-APERTURE DIPOLE

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ABSTRACT

The Large Hadron Collider (LHC) is proposed at CERN as the next facility to push further the frontier of high energy physics. The design of the superconducting dipole magnets is based upon the "two in one" concept in which the dipoles of the two rings of the collider have a common magnetic circuit. Twin aperture models (MTA1) designed for a 10 T field level are being developed in collaboration with European Industries. These high field magnets require a sophisticated mechanical design of the various parts as collars, split iron yoke and outer shrinking cylinder. A structural analysis of the MTA1 magnets has been made at CERN by using the FEM code "ANSYS". We report on the mechanical analysis and optimization of the magnet during assembly, cooldown and under the electromagnetic forces.

INTRODUCTION

The design of the superconducting magnets for a Large Hadron Collider (LHC), which is proposed at CERN [1] is based upon the "two in one" concept. In this configuration, the two dipole magnets of the two rings have a common magnetic circuit. This solution is economical in space and cost and should allow the installation of very high field dipoles in the existing LEP tunnel at CERN. The envisaged field level for LHC is in the range 8 to 10 T. A R. & D. programme is pursued at CERN to reach this goal [2]. To demonstrate the feasibility of the LHC machine, 10 T twin-aperture models and prototypes have to be constructed and tested.

Four one-meter long models are now under construction in collaboration with industries: ANSALDO (Italy), ELIN (Austria), HOLEC (Netherlands), JEUMONT-SCHNEIDER (France). The four

models, which make use of NbTi superconducting cables working at 2 K, have various technical solutions and are based on the design report presented in Ref. [3]. The present report deals with more detailed analysis of the mechanical structure of the straight part of the 10 T twin-aperture superconducting dipole. The mechanical structure is designed to sustain an horizontal resultant of magnetic forces corresponding to 11.2 T field. The main parameters of the 10 T twin-aperture dipole are summarized in Table 1.

DESCRIPTION OF THE MECHANICAL STRUCTURE AND DESIGN PRINCIPLES

Fig. 1 shows the cross section of the magnet. The coil support structure is formed by :

- A twin collar made of Al alloy in which the coils are assembled and prestressed at ~ 55 MPa at room temperature.
- An iron yoke, split in two parts at the vertical symmetry plane of the twin-aperture magnet. The two iron inserts between collars and yoke at the vertical plane serve to reduce the quadrupole component due to iron saturation.
- A stainless steel or aluminium alloy outer cylinder around the yoke.

TABLE 1

Dipole Parameters at 2 K	
Bore field [T]	10
Current [A]	15000
Turns per beam channel	
1st layer	2 x 13
2nd layer	2 x 24
Overall current density	
1st layer	357.5 A/mm ²
2nd layer	532.9 A/mm ²
Coil inner diameter	50 mm
Coil outer diameter	120.2 mm
Distance between aperture axes	180 mm
Collars outer dimensions	381x201 mm
Iron outer diameter	540 mm
Stored Energy for both combined channels	684 kJ/m
Resultant of magnetic 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

Fig. 1 - Cross section of MTAl magnet.

1. Coils, 2. Al collars, 3. Yoke, 4. Iron insert, 5. Clamp, 6. Gap, 7. Outer shrinking cylinder.

The two parts of the yoke are separated by a gap at room temperature and so adjusted that, after cool down, two necessary conditions are fulfilled :

1. The collars and the yoke are in contact along the horizontal axis so that the horizontal component of the magnetic forces is well sustained by collars and yoke.
2. A required compressive force is produced on the mating faces of the yoke parts. The compressive force will be so that the gap stays closed at full excitation of the magnet.

In these conditions, the resulting mechanical structure is very rigid and has therefore smaller outward displacements under the large magnetic forces and consequently small stresses are induced in the coils by the bending moment effects. Moreover, when the inward displacement of the iron in the horizontal direction is larger than the corresponding shrinkage of the collared coils during cool down, an additional non-uniform prestress is introduced on the coils at low temperature.

The possibility to have, after cool down, a compressive force on the mating faces of the half-yokes and a closed contact between the collars and the yoke depends on the relative dimensions of the components of the structure, the choice of materials, the prestress in the outer shrinking cylinder and the dimension of the gap between the two half-yokes.

The wanted gap is fixed and controlled at room temperature by means of clamps which maintain the two half-yokes at the desired position. After the assembly of the outer shrinking cylinder, the clamp force is transferred to the outer cylinder.

The difference between the required

stressing of the coils at operating conditions and the loading produced by the cool down of the structure determines the prestress which has to be provided at room temperature by coil collaring. The guide line for the stresses in the coils at full excitation is to have no region of the coil under tensile stresses and to keep the coils in contact with the collars [4]. Moreover, to limit the creep effects in the coils (flow of insulating materials) it is of great importance to have the prestress as small as possible at room temperature. If one assumes an infinitely rigid mechanical structure and neglects the stresses due to bending moments in the coils, a first idea of the minimum prestress in the coils at room temperature is given by :

$$\sigma_{\theta,0,\text{coil}} \approx \varepsilon \frac{F}{2w} - \Delta\alpha \cdot E_{\text{coil}} \approx 31\text{MPa}$$

in which $w = 17.3 \text{ mm}$ is the width of the insulated cable $E_{\text{coil}} = 20 \text{ GPa}$ is the apparent Young's modulus of the coil, $\Delta\alpha$ is the difference of the integrated thermal contraction coefficient between 2 K and 300 K for coils and collars.

This relation ensures the contact between the coil and the collars at the upper angle of the coil layers.

OPTIMIZATION OF THE MECHANICAL STRUCTURE

Calculations of the mechanical structure have been made using the computer code Ansys[5]. Fig. 2 shows the general mesh for the LHC magnets used in the calculations. The collars are supported in the vertical and horizontal plane. There is a clearance of 0.5 mm between collars and iron yoke. The interferences between the various parts of the mechanical structure are simulated by "gap elements" provided in Ansys code.

The stresses and deformations have been calculated following the various sequences of the assembly : collaring, clamping, outer cylinder assembly, excitation at 11.2 T. The major results are summarized in Table 2 for the external cylinder made of Al alloy. The various points where stresses or dis-

Fig. 2 - Mesh used in Ansys code.

Fig. 3 - Sketch with the various points presented in Table 2 and Table 3.

placements are reported as indicated on Fig. 3. The presented results deal with the right part of the coils. The calculations refer to 1 mm of magnet length.

Coil Prestressing by collaring

The required prestressing obtained at room temperature by collaring the coils is simulated by the insertion of

TABLE-2 - SUMMARY OF THE MAIN RESULTS FOR MTA1

Material of the outer cylinder :		Al alloy, 18.5 mm thick				
Dimensions of the tapered iron half gap		0.51/0.44 mm				
		Collaring	Clamp	Clamp + outer cylinder	Cool-down	Excitation
Conditions						
Temperature	K	293	293	293	2	2
Tcylinder	K			258	(- 33)	(- 33)
Field	T					11.2
Outer cylinder						
σ_{cyl}	Mpa			19	94	95
Fcyl	N			346	1739	1757
Yoke						
Fm	N				- 1505	- 180
ΔFm	N					+ 1325
Fi	N		- 327	- 328	- 485	- 1029
$\Delta x(A)$	mm		- 0.103	- 0.103	- 0.52	- 0.52
$\Delta y(A)$	mm		- 0.001	- 0.007	- 0.63	- 0.658
$\Delta x(B)$	mm		- 0.09	- 0.102	- 0.44	- 0.44
$\Delta y(B)$	mm		0.0001	0.001	- 0.318	- 0.337
$\Delta x(C)$	mm	- 0.013	- 0.07	- 0.077	- 0.803	- 0.725
$\Delta x(D)$	mm		- 0.078	- 0.086	- 0.964	- 0.899
Collar						
Fc	N		- 373	- 429	- 223	- 1599
ΔFc	N					- 1376
$\Delta y(E)$	mm	0.298	0.394	0.397	- 0.006	- 0.048
Coils						
$\sigma(1)$	MPa	- 31	- 32	- 32	- 41	- 7
$\sigma(2)$	MPa	- 35	- 35	- 35	- 45	- 99
$\sigma(3)$	MPa	- 56	- 59	- 60	- 76	- 29
$\sigma(4)$	MPa	- 54	- 56	- 56	- 70	- 96
$\sigma(5)$	MPa	- 77	- 67	- 66	- 83	- 132
$\Delta x(F)$	mm	- 0.0005	- 0.053	- 0.06	- 0.624	- 0.508
$\Delta x(G)$	mm	- 0.008	- 0.005	- 0.005	- 0.129	- 0.167
$\Delta \phi$	mm					- 0.154

shims at the horizontal plane of the coils. Due to the prestressing, the collars are deformed. The interference between the collars and the iron yoke is checked so that the relative displacement of the various parts is not prevented during cool down.

Tapered shims with an angle of $\sim 0.25^\circ$ and 0.13° should allow more homogeneous distribution of the azimuthal stresses in the coil.

A separate model of the collars has been studied to see their behaviour in 3D. Fig. 3 and Fig. 4 show the deformation of collars and the stresses in

coils after collaring. The stresses in the collars around the longitudinal rods are high and could reach locally the plastic deformation. This deformation will be taken into account in the determination of the shims between coils and collars. Special care has to be taken when the rods are inserted in the collars to avoid excessive overstressing of the coils during collaring.

Clamping of the Yoke

The two half-yokes are pressed on the collared coils at 370 N and precisely machined clamps are inserted. The

Fig. 4 Deformation of coils after collaring.

Fig. 5 - Stresses in coils after collaring (N/mm²)

gap between the half-yokes can then be verified. In this procedure, the collars move by 0.07 mm and the half gap closes by 0.103 mm so that the initial tapered gap of 0.52/0.44 mm becomes 0.42/0.35 mm when the clamp is installed. The hori-

zontal radius of the yoke is reduced by 0.078 mm. The azimuthal stresses in the coils vary slightly.

Prestressing of the outer Cylinder around the Yoke

The required prestressing of 20 MPa in the outer cylinder at room temperature is simulated in Ansys by a shrink-fitting with a $\Delta T = 35$ K, which corresponds to $\Delta R = -0.13$ mm. The ratio between the stiffness of the collars and the outer cylinder is so that ΔR is shared almost equally between the two elements. The force previously taken by the clamp is then transferred to the outer cylinder and no change occurs in the structure.

Cool-down at 2 K

At the cool-down, the outer cylinder drives the structure so that a mating force of 1505 N appears between the two half-yokes in the vertical plane and a compressive force on the collars of 223 N in the horizontal direction and 485 N in the vertical direction. The mean azimuthal stress in the coils is increased by 15 MPa on the inner layer and 10 MPa on the outer layer. During cool-down, the iron yoke rotates following the vertical contraction of the collar. This rotation enhances the displacement of the gap by 0.13 mm at the top of the gap and by 0.07 mm at the bottom of the gap. After cool-down, the magnet is no longer circular by 0.33 mm in radius. The stresses in collars reach 90 MPa at the upper angle of the outer layer.

Excitation at B = 11.2 T

It can be seen that the outward electromagnetic force (2940 N) is shared nearly equally between collars and iron structure (1325 and 1376 N). The radial deformation in the median plane of the collared coil at excitation is 0.078 mm. With collars only, the displacement would have been 0.289 mm. The displacement of the coils themselves is 0.116 mm for the right side and 0.038 mm for the left side so that the magnetic axis moves by 0.078 mm.

At the excitation of 11.2 T, the iron gap stays closed and, as foreseen, there is practically no change in the outer cylinder stresses.

It can be seen that the coils are still in a compressive state and the maximum stress is 132 MPa on the inner

radius at the median plane.

Stainless steel outer cylinder

Calculations have been made when the outer cylinder is made of stainless steel, 12 mm thick. Due to the lower contraction, the prestress in the cylinder has to be increased so that the yoke stays in contact with the collars after cooldown. If the collars were infinitely rigid, the prestress would be ~ 250 MPa or $\Delta T = 120$ K for the simulation in ANSYS. After assembly of the outer cylinder on the iron and collars, the prestress is 116 MPa at room temperature. When the clamp is installed with a force of 1400 N, the initial tapered half-gap of 0.52/0.44 mm becomes 0.20/0.20 mm. The collars are displaced by 0.2 mm and the stress distribution varies mainly in the inner layer. Compared with the Al alloy case, the compressive stress is increased by 9 MPa at the upper angle (point 3), but is decreased by 16 MPa at the median plane-inner radius (point 5). However, radial stresses of 50 MPa appear in the outer layer. After cool-down, the situation is similar to the one with an Al alloy cylinder. At 11.2 T, the stresses in the stainless steel cylinder do not exceed 162 MPa.

CONCLUSIONS

1. The mechanical calculations made with ANSYS on the straight part of the magnet indicate that the mechanical structure of the twin aperture 10T dipole performs well up to 11.2T.

2. The mechanical structure resulting from the assembly of collars/yoke/shrinking cylinder provides a deformation of the collared coils less than 0.08 mm at 11.2 T (0.06 mm at 10 T). The overall rigidity is increased by a factor 3.7 by the effect of the iron and outer cylinder. It has to be mentioned that the vertical support of the iron increases the rigidity by a factor 2.15. The gap stays closed up to a field of 11.8 T. The use of stainless steel collars which would increase the overall rigidity by a factor 1.75 would require a supplementary prestress of 8 MPa in the coils at collaring.

3. The stresses in collars are maximum at room temperature around the rods. The collaring procedure has to be well controlled to avoid overstressing of the coils. Fatigue tests have to be made on the collars.

4. The maximum compressive stress which is 130 MPa at 11.2 T (120 MPa at 10 T) could be reduced at 110 MPa for a magnet working at maximum 10 T if the coil prestressing at room temperature is reduced accordingly. Moreover an increase in prestress of 500 N in the outer cylinder would decrease the maximum compressive stresses by ~ 6 MPa in the median plane of the inner layer.

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