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**Title: MAGNETIC FIELDS AND LORENTZ FORCES IN AN LHC DIPOLE MAGNET;
 3-D ANALYSIS USING THE FEM PROGRAM TOSCA**

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**MAGNETIC FIELDS AND LORENTZ FORCES IN AN LHC DIPOLE MAGNET;
3-D ANALYSIS USING THE FEM PROGRAM TOSCA.**

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ABSTRACT

This paper describes an investigation of magnetic fields and lorentz forces in the straight section and the coil end of an LHC-dipole magnet using the finite element program TOSCA. Starting from an existing design of the straight section the constant perimeter description was used to generate the coil end geometry. Results will be shown of the local magnetic field and lorentz force in the coil end.

INTRODUCTION

The design of the CERN-LHC dipole magnets is characterised by the effort to attain the highest possible magnetic field in the twin bores of the magnet (see fig. 1). In order to optimize the use of superconductor and to ensure a safe performance, the two layers of the coils should simultaneously reach their critical current as a function of the local maximum field. This requires a detailed study of magnetic fields in the conductor region of the magnet. Usually, the peak field of a dipole occurs in the magnet end, where the windings have a complex geometry and the tensile stress in the conductor has a maximum. The complex geometry of the ends inhibits proper support of the conductor. Therefore, it is the end part that limits the performance of the magnet. To prevent this, the maximum field occurring in the ends should be reduced. This can be achieved by an increment of the inner radius of the iron yoke in the end part of the magnet. A 3-D calculation of the magnetic field in the end part should reveal the reduction of the peak field due to this increment. Also, the lorentz forces on the conductors must be calculated in order to get the total force in the

longitudinal direction of the magnet. The calculations were performed on the design of the 1 meter prototype LHC dipole magnet. For this we used the software package called TOSCA [1], a finite element program that solves electromagnetic problems in 3-D.

MODELING

The main advantage of using a finite element method is that a $B(H)$ function can be specified in the program, which allows the study of magnetization in the iron at any value of the magnetic field. As a consequence, a non-linear $B(I)$ relation will appear in contrast to analytical calculations where B/I is always constant due to the required assumption that μ_r is infinite. A second important benefit is the possibility of precise modeling of the iron yoke. For analytical calculations a symmetric structure must always be assumed in order to use the method of image currents [2]. Fig. 2 shows the geometry of the iron as used in the calculation. Considering the symmetry in the 2-in-1 magnet, only one 8th part of the volume of this magnet (one octant) needs to be considered. The geometry of the conductors

FIGURE 1 Cross section of the CERN-LHC 10 T prototype dipole magnet. The enlarged part shows the conductors.

FIGURE 2 View of the iron as modeled by TOSCA. Only one 8th of the volume of the magnet needs to be studied.

in the magnet ends is very difficult to describe mathematically if keystone Rutherford type cables are used, as is the case for the LHC model magnets. Therefore a convenient model must be applied to approximate the real shape. In our case the so-called constant perimeter description [3] was chosen. In this description all parts of the conductor have the same perimeter in the coil end. In TOSCA a module is present which approximates this constant perimeter model. This is due to the fact that in thick conductors on a relatively small bending radius the constant perimeter condition cannot be fulfilled for all parts of the conductor. We used the condition that all central points of the conductor, located on the central radius, have the same perimeter. The algorithm used in TOSCA to create the constant perimeter end is described briefly as follows. A milling cutter, which

maintains a constant angle to the magnet axis, is moved over the winding cylinder. The path described by the cutter gives the geometry of the conductor on the winding cylinder. The result is that a conductor always consists of two parallel lines in radial direction and two concentric segments of circles. The path of the axis of the cutter, developed on the winding cylinder is in our case a half circle. As the algorithm uses a parameterisation for the conductors, the field induced by the current in a conductor can be obtained with a predefined accuracy by numerical integration. In order to reduce the CPU time mainly necessary for the integration, the number of conductors should be minimised. Therefore, a complete block of conductors in the magnet is modeled as one constant perimeter conductor, using the same current density as in the separate conductors. Although this may seem to give

inaccurate results, one should realize that the local magnetic field is composed of the contributions of all the conductors in the magnet. Comparing the values of local magnetic field in the straight part of the magnet with accurate 2-D calculations [4], where the same $B(H)$ dependence was used, showed that the differences are less than 2%. In order to improve the approximation of the shape of the upper conductor in the outer layer of the LHC-design, this conductor was split up in three parts and modeled as three separate conductors. A consequence of the use of the constant perimeter description in TOSCA is that the magnetic field inside the magnet cannot be analysed in terms of multipole components. This has been the subject of a separate study [5].

RESULTS

Magnetic fields

With a current of 14556 A per cable a central field of about 9.88 T was obtained. Therefore, for 10 T we need 14736 A, which corresponds to an overall current density in the inner and outer layer of 341 A/mm^2 and 526 A/mm^2 respectively. The maximum field in the two layers in the straight part of the magnet occurs at the top edge of the top conductors of the layers. For the inner layer the maximum is found exactly on the inside corner and amounts 10.22 T for a central field of 10 T. In the outer layer, the maximum is found at about 2 mm outward from the inside corner and amounts 8.66 T. Fig. 5 shows B_y along the magnet axis. The straight section of the magnet has a length of 0.68 m and the longest conductor has a length of 1.03 m. The calculated magnetic length of the

magnet, defined as

$$L_{\text{mag}} = \int_{-\infty}^{\infty} B_y(0,0,z) dz / B_y(0,0,0),$$

was found to be 0.87 m. The magnetic field in the outer conductors is not significantly changed if the length of the straight part of the conductors in the outer layer is increased by 1 cm. To check the sensitivity of the value of the magnetic field to small geometry changes the inclination angle of conductor 4 was changed. This angle which is the angle between milling cutter and winding cylinder was reduced by 10 degrees. This should alter the path of this conductor in the end. No significant change in the magnetic field value was found. It seems that the local magnetic field is not mainly determined by the local shape of a conductor, but by the added contributions of all conductors.

The maximum field in the magnet end is usually an absolute maximum and is found on the innermost conductor (closest to the winding cylinder top) just before the conductor starts the bending over the winding cylinder as indicated in fig. 3. The effect of an increment of the inner radius of the iron yoke in order to reduce the peak field in the magnet end is demonstrated in figs. 4 and 5. The inner radius of the iron in the end part was increased from 100 mm to 128 mm. For the inner conductor layer the maximum in the field plot disappears completely. In the outer layer only a small maximum is left which is less than 0.1 T greater than the field in the straight part of the magnet. Additionally, calculations were performed with an inner radius of the iron in the magnet end of 135 mm. Table 1 presents the effect of the increase of this radius. It

FIGURE 3 The dipole field B_y along the magnet axis.

FIGURE 4 Position of the maximum field in the end part of the magnet.
(inner conductor layer)

FIGURE 5 The effect of an increase of the inner radius of the iron (step) on the max. field occurring in the inner conductor layer of the magnet.

FIGURE 6 The effect of an increase of the inner radius of the iron (step) on the max. field occurring in the outer conductor layer of the magnet.

is clear that a satisfactory reduction of the peak field is already obtained by increasing the inner radius of the iron to 128 mm, and probably it is sufficient to use a smaller increment.

TABLE 1
Effect of the increase of the inner radius of the iron yoke in the magnet end.

inner radius [mm]	max. field inner layer [T]	max. field outer layer [T]
100	10.26	9.02
128	10.02	8.70
135	9.99	8.69

In order to study the field contribution of the magnet end, the length of the straight part of the magnet was varied. The load current for a central field of 10 T as a function of the length L

of the straight part of the magnet amounts:
 $I = 14736 \text{ A}$ for $L = 0.68 \text{ m}$, (model magnet),
 14778 A $L = 6.8 \text{ m}$ and
 14792 A $L = 16.8 \text{ m}$.

It is clear from these data that the magnet end gives a larger contribution to the central field than the distant part of the straight section. Compared to the analytical calculation [2], the current surplus, or saturation factor, amounts 2.3%. This is in excellent agreement with the 2-D calculations [4], where a saturation factor of 2.2% was found.

Lorentz forces

Figs. 6,7 show for two conductors the force per unit of length of conductor in the magnet end as a function of the angle φ . This is the angle between milling cutter and the line in the ϕ - z plane where the conductor end part starts; $\varphi = 0$ at the beginning of the end part and $\varphi = 90$ on top of the winding cylinder. The force in the y -direction in conductors 4 and 8 is directed to the axis of the magnet. However, the total force is always directed

FIGURE 7 The force per unit length of conductor in the centre of the upper conductor (nr. 4, see Fig. 9) in the inner layer as a function of φ .

FIGURE 8 The force per unit length of conductor in the centre of the upper conductor (nr. 8, see Fig. 9) in the outer layer as a function of φ .

FIGURE 9 Plot of the total force vectors per octant of the magnet end part.

in the azimuthal direction of the conductors or outwards. It was checked that this is the case independent of the z-position. Fig. 8 shows the direction of the total force on the end part of one octant of the magnet. Table 2 gives the total force in the magnet end part.

TABLE 2

Total lorentz force per conductor in one octant of the magnet end part, at a central field of 10 T. Forces in kN.

cond	F_x	F_y	F_z	F_{tot}
1	8.5	0.8	4.5	9.6
2	12.4	1.0	8.6	15.1
3	8.1	-1.3	7.4	11.0
4	3.0	-0.4	2.9	4.2
5	-1.1	-6.0	5.7	8.3
6	5.3	-10.3	10.6	15.6
7	12.1	-13.4	17.3	25.0
8	17.8	-12.2	21.0	30.1

CONCLUSIONS

It was shown that an increase of the inner radius of the iron yoke in the end part to 128 mm reduces the local peak field. The local value of the magnetic field in the end part is not mainly determined by the local shape of a conductor but by the added contributions of all conductors. Small geometry changes should therefore not change the solution. The force on the conductors is always directed in the azimuthal direction or outwards. Therefore, there is no need for an inner supporting structure. The total force in the z-direction per dipole amounts 311 kN at a central field of 10 T.

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