Measuring the Magnetic Field Inside the CMS Steel Yoke Elements

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***Abstract*–The Compact Muon Solenoid (CMS) is a general-purpose detector designed to run at the highest luminosity at the CERN Large Hadron Collider (LHC). Its distinctive features include a 4 T superconducting solenoid with 6 m diameter by 12.5 m long free bore, enclosed inside a 10000-ton return yoke made of construction steel. The return yoke consists of five dodecagonal three-layered barrel wheels and four end-cap disks at each end comprised of steel blocks up to 620 mm thick, which serve as the absorber plates of the muon detection system. Accurate characterization of the magnetic field everywhere in the CMS detector is required. To measure the field in and around the steel a system of 22 flux-loops and 82 3-D Hall probe B-sensors is installed on the return yoke blocks. Fast discharges of the solenoid (190 s time-constant) made during the CMS magnet surface commissioning test at the solenoid central fields of 2.64, 3.16, 3.69 and 4.01 T were used to induce voltages in the flux-loops. The voltages are measured on-line and integrated off-line to obtain the magnetic flux in the steel yoke close to the muon chambers at full excitations of the solenoid. The Hall probe B-sensors installed on the steel-air interfaces give supplementary information on the components of magnetic field and permit to estimate the remanent field in steel to be added to the magnetic flux density obtained by the voltages integration. A TOSCA 3-D model of the CMS magnet is developed to describe the magnetic field everywhere outside the tracking volume measured with the field-mapping machine. The results of the measurements and calculations are presented, compared and discussed.**

I. INTRODUCTION

THE muon system of the Compact Muon Solenoid (CMS) includes a 10,000-ton yoke comprised of the construction steel plates up to 620 mm thick, which return the flux of the 4 T superconducting solenoid and serve as the absorber plates of the muon detection system [1], [2], [3].

A three-dimensional (3-D) magnetic field model of the CMS magnet has been developed [4] for the track parameter reconstruction when the detector begins operation. The model is calculated with TOSCA [5], it has been normalized to the magnetic field measurements [6] done inside the CMS coil with the field-mapping machine at five central field values of 2, 3, 3.5, 3.8, and 4 T, and this model is used to prepare the CMS magnetic field map everywhere outside the measured volume.

A direct measurement of the magnetic flux density in selected regions of the yoke is provided with 22 flux-loops to estimate the uncertainty of utilization of the calculated values for the magnetic field to be used to determine the momenta of muons during the detector operation. The flux-loops of 315÷495 turns have been wound around selected blocks of the CMS yoke plates to measure the magnetic flux changes induced by the "fast" (190 s time-constant) discharges of the CMS coil made possible by the protection system, which is provided to protect the magnet in the event of major faults [7], [8]. An integration technique [9], [10] was developed to reconstruct the average initial magnetic flux density in steel blocks at the full magnet excitations, and the contribution of the eddy currents was calculated with ELECTRA [11] and estimated on the level of a few per cent [12].

In the present paper we summarize the results of the magnetic flux measurements done with the flux-loops and compare the obtained results with the calculations performed with the TOSCA CMS magnet model.

II. THE CMS MAGNET MODEL DESCRIPTION

The CMS magnet model corresponding to the CMS configuration used for the magnet surface test is presented in Fig. 1. The model comprises the coil four layers of the superconductor and a half of the magnet yoke that consists of five barrel wheels of the 6.995 m inscribed outer radius and 2.536 m width, two nose disks of 2.63 m radius and 0.936 m thickness on each side of the coil, three large end-cap disks of the 6.955 m inscribed radius on each side of the magnet, and one small end-cap disk of 2.5 m radius on one side of the magnet.

Each barrel wheel except the central one has three layers of steel connected with brackets. The central barrel wheel comprises a fourth most inner layer, called tail catcher, made of steel and turned by 5 degrees in the azimuth angle with respect to dodecagonal shape of the barrel wheels. The coordinate system used in the model corresponds to the CMS reference system where the X-axis is directed in horizontal plane toward the LHC center, the Y-axis is upward, and the Z-axis coincides with the superconducting coil axis.

The thickness of the tail catcher blocks is 0.18 m, the thickness of the first barrel layer is 0.29 m, both second and third barrel layers has a thickness of 0.62 m. The air gap

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Manuscript received November 4, 2008.

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between the tail catcher and the first barrel layer is 0.567 m, the air gap between the first and second barrel layers is 0.445 m, and the air gap between the second and third barrel layers is 0.405 m. All these air gaps are used to install the muon drift tube chambers and resistive plate chambers to register the muon particles.

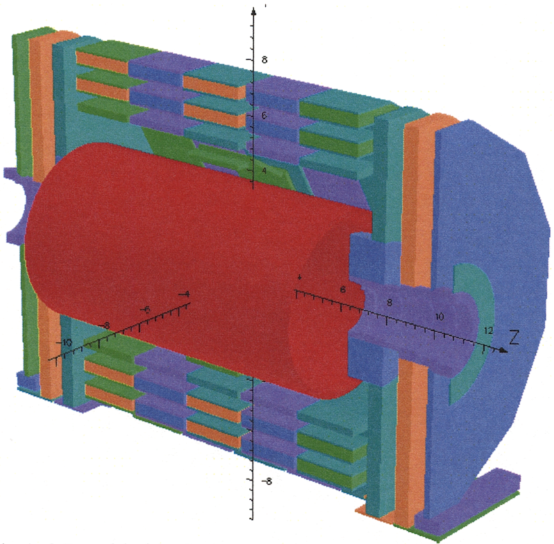

Fig. 1. 3-D model of the CMS magnetic system

The barrel wheels are denoted as follows: YB/0 is for central wheel, YB/±1 are for the next to central wheels, YB/±2 are for two extreme barrel wheels. The air gaps between YB/0 and YB/±1 are 0.15 m and the air gaps between YB/±1 and YB/±2 are 0.12 m. The barrel wheels feet and the connecting brackets between the barrel layers are included in the model.

The thickness of two first, YE/±1 and YE/±2, end-cap disks on each side of the coil is 0.592 m, the thickness of the third disks, YE/±3, is 0.232 m, and the thickness of the fourth small disk YE/+4 is 0.075 m. The air gaps between YB/±2 and YE/±1 are 0.659 m, the air gaps between YE/±1 and YE/±2 are 0.663 m, the air gaps between YE/±2 and YE/±3 are 0.668 m, and the air gap between YE/+3 and YE/+4 is 0.664 m. All these air gaps are used to install the muon cathode strip chambers and resistive plate chambers.

Both nose disks, YN/±1, are partially inside the coil. The distance between YN/–1 and YN/+1 is 12.666 m that corresponds to the YE/±1 and YN/±1 shape after deformation under the magnetic forces at the CMS magnet full excitation. The end-cap disk carts upper plates of 0.1 m thickness are included in the model.

A. *Coil Description*

The CMS coil consists of five modules of 2.5 m long, and at the room temperature has the designed length of 12.514 m and inner diameter of 6.3196 m. Four layers of superconductor make the coil thickness of 0.2632 m. In the model the coil dimensions are considered at the temperature of 4°K and the scale factor of 0.99585 is applied to all the dimensons. The change of the coil shape under the magnetic pressure is also taken into account. Thus, in the model, the mean radii of the superconductor layers in the central coil module CB/0 are 3.18504, 3.25017, 3.3153, and 3.38043 m. In two adjacent coil modules CB/±1 the mean radii of the superconducting layers are 2 mm less, and in the two extreme coil modules CB/±2 the corresponding mean radii are 5 mm less than in the central coil module. There is one missing turn out of 2180 designed turns in the most inner layer of the CB/–2 module between Z=–3.76493 and Z=3.8 m, thus the magnetic field produced by the CMS coil is slightly asymmetric with respect to the coil middle plane at Z=0 m.

B. *Steel Magnetic Properties Description*

Three different B-H curves of the construction steel of the CMS magnet yoke are used in the model. The first curve describes the magnetic properties of the 0.45 m thick plates in the second and third barrel wheels layers. The second curve describes the magnetic properties of 0.085 m thin plates around the thick plates of the second and third barrel wheels layers, and also the properties of the plates of the first layers and the tail catcher plates of the barrel wheels. Finally, a third curve describes the magnetic properties of the nose and end-cap disks and the cart plates.

C. *Model Normalization*

The model is normalized to the magnetic flux density at the coil center, measured with the CMS field-mapping machine [6]. To obtain the same central value of the magnetic flux density in the model, a scale factor of 1.006 is applied to the coil measured current.

The model contains 21 conductors and 1,922,958 nodes of the element mesh.

III. FLUX-LOOPS DESCRIPTION

The CMS magnet yoke is made of construction steel that contains up to 0.17% C, up to 1.22% Mn, and also some Si, Cr, and Cu. To reconstruct the magnetic flux density at the CMS magnet excitations before the fast discharges of the coil, 22 flux-loops have been wound around ten blocks of the barrel wheels YB/0, YB/–1, YB/–2 of the bottom 30° azimuthal sector and around two bottom 18° azimuthal sectors of thick end-cap disks YE/–1 and YE/–2. The flux-loops are performed from the flat ribbon cable of 45 wires that has been wound 7÷11 times around the blocks. The areas enclosed by the flux-loops vary from 0.3 to 1.58 m^2 on the barrel wheels and from 0.5 to 1.13 m^2 on the end-cap disks.

To read out the voltages induced in the flux-loops by changing the magnetic flux in the blocks during the coil fast discharge, seven USB-based DAQ modules USB-1208LS of Measurement Computing [13] with 4 differential 12-bit analog inputs each are used. The precision of the voltage measurements is (1.5±1.5) % in terms of the standard deviation.

The USB-1208LS DAQ modules are attached by the USB cables to two network-enabled AnywhereUSB®/5 hubs [14] connected to the personal computer through 3Com®

OfficeConnect® Dual Speed Switch 5 [15] sitting on a local Ethernet network cable of 90 m.

IV. COMPARISON OF THE MEASURED AND CALCULATED MAGNETIC FLUX DENSITY IN STEEL

The average magnetic flux density in steel blocks of the CMS magnet yoke is reconstructed by the off-line integration of the voltages induced in the flux-loops during the coil fast discharges made from the current values of 12.5, 15, 17.55, and 19.14 kA. These current values produce the magnetic flux density at the CMS coil center of 2.64, 3.16, 3.79, and 4.01 T, accordingly. The shape of the coil current vs. time is displayed in Fig. 2. Those current discharges lead to changing the magnetic flux inside the yoke steel elements that induces the voltages in the flux-loops with the amplitudes up to 3÷4.5 V [6].

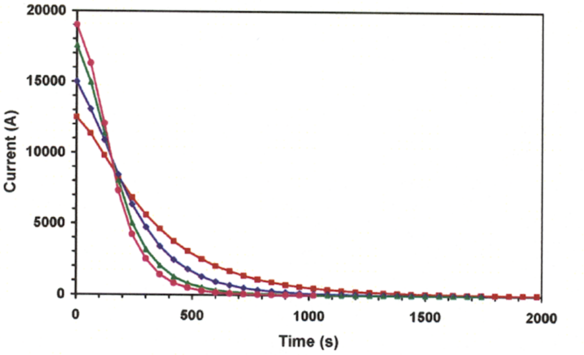

Fig. 2. CMS coil fast discharges made from 12.5, 15, 17.55, and 19.14 kA.

The remanent fields of 54÷85 mT are added then to the magnetic flux densities obtained by the voltages off-line integration to estimate the total averaged field values in steel blocks at the maximum currents being before the coil fast discharges. These remanent fields were obtained from the B-H curves measurements performed for all the types of steel used in the CMS yoke and, in particular, corresponded to the magnetic properties of steel blocks where the flux-loops are mounted.

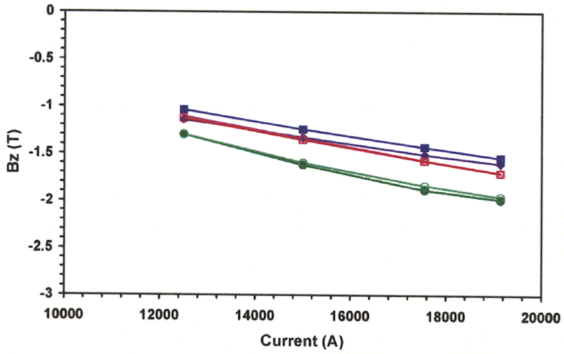

Fig. 3. Axial magnetic flux density measured (dark green, blue, and violet) and calculated (light green, red, magenta) in three layers of the central barrel wheel YB/0 vs. the coil current.

In Figs. 2 and 3 the measured values of the magnetic flux density vs. the maximum current values are presented and compared with the calculated field values in the same blocks of the YB/0 central barrel wheel and YE/–2 end-cap disk. All the flux-loops of the central barrel wheel are mounted at Z=0 m; the flux loops at both end-cap disks are mounted at the inscribed radii 2.8, 4.565, and 6.235 m off the coil axis. In other the barrel wheels the flux-loops are mounted at the Z-coordinate values of -2.686, -4.214, -5.342, and -6.47 m.

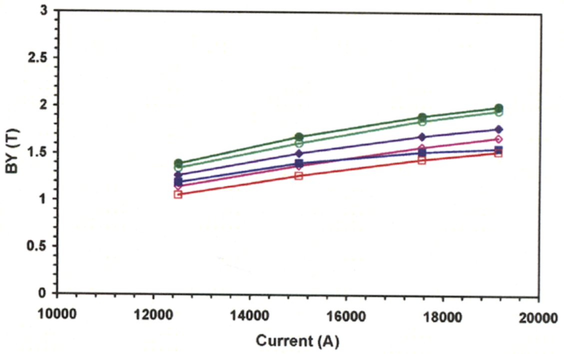

Fig. 4. Radial magnetic flux density measured (dark green, blue, and violet) and calculated (light green, red, magenta) in three cross-sections of the YE/–2 end-cap disk vs. the coil current.

The comparison of the measured and calculated magnetic flux density in steel blocks of the CMS yoke gives a difference between these values of 10% in average in terms of the standard deviation. In the yoke steel elements located closer to the coil axis the measured magnetic flux density is systematically higher than the calculated field; in the outer steel blocks the comparison gives an opposite result. These differences could not be described in terms of the eddy currents contributions [12].

V. COMPARISON OF THE MEASURED AND CALCULATED MAGNETIC FLUX DENSITY IN AIR

Measurement of the magnetic flux density is also done in the air gaps of the YB/±2 barrel wheels used for the barrel muon drift tube chambers location.

The measurements are performed at the coil central field of 4.01 T with nine 3-D Hall B-sensors, produced at NIKHEF and calibrated at CERN to a precision of $5\cdot10^{-4}$ at a field of 1.4 T [16]. Six B-sensors have been placed on an aluminum bar structure installed on YB/–2 barrel wheel and been able to move the sensors along the radius at the azimuth angle of 210° to measure three components of the field at 18 different points. Another three B-sensors have been installed on the muon drift tube chambers of the barrel wheel YB/+2.

For the measurements performed in the air gaps the average difference between the measured and calculated field values is 1.8% in terms of the standard deviation.

VI. CONCLUSIONS

The magnetic flux density is measured in steel blocks of the CMS yoke at the coil central field values of 2.64, 3.16, 3.79, and 4.01 T.

The precision of measurements performed with the flux-loops in the CMS yoke steel blocks is a few per cent. The CMS magnet model calculations differ from the field values measured with the flux-loops in steel by 10% in average in terms of the standard deviation.

The measurements done in the air gaps between the barrel wheels steel blocks at the coil central field value of 4.01 T differ from the calculated values by 1.8% in average in terms of the standard deviation.

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