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Flux Loop Measurements of the Magnetic Flux Density in the CMS Magnet Yoke

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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 a 12.5-m-length free bore, enclosed inside a 10,000-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. To measure the field in and around the steel, a system of 22 flux loops and 82 3-D Hall sensors is installed on the return yoke blocks. A 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 first attempt is made to measure the magnetic flux density in the steel blocks of the CMS magnet yoke using the standard magnet discharge with the current ramp down speed of 1.5 A/s.

Keywords Flux loops · Hall probes · Magnetic field measurements · Superconducting solenoid

1 Introduction

The muon system of the Compact Muon Solenoid (CMS) detector 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 [1–4]. During the Large Hadron Collider (LHC) long shutdown occurring in 2013/2014, the CMS magnet yoke was upgraded with the additional 14-m-diameter end-cap disks at the extremes of the muon detection system [5].

The magnetic flux density in the central part of the CMS detector, where the tracker and electromagnetic calorimeter are located, was measured with a precision of $7 \cdot 10^{-4}$ with the field-mapping machine at five central field values of 2, 3, 3.5, 3.8, and 4 T [6]. To describe the magnetic flux everywhere outside the measured volume, a three-dimensional (3-D) magnetic field model of the CMS magnet has been developed [7] and calculated with TOSCA program [8]. The model reproduces the magnetic flux density distribution measured inside the CMS coil with the field-mapping machine within 0.1 % [9]. The modification of this model for the upgraded CMS magnet yoke was validated by comparing the calculated magnetic flux density with the measured one in the selected regions of the CMS magnetic system [10].

A direct measurement of the magnetic flux density in the selected regions of the yoke was provided during the CMS magnet test of 2006 with 22 flux loops of 315 to 450 turns wound around the yoke blocks. 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 [11, 12], induced in the flux loops the voltages caused by the magnetic flux changes. An integration technique [13, 14] was developed to reconstruct

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the average initial magnetic flux density in steel blocks at the full magnet excitation, and the contribution of the eddy currents was calculated with ELEKTRA program [15] and estimated on the level of a few percents [16].

The results of the magnetic flux measurements done with the flux loops and the comparison of the obtained values with the calculations performed with the previous CMS model are described elsewhere [17].

In the present paper, we compare the calculations based on the recent CMS magnet model with the measurements performed with the flux loops in the yoke steel and with the 3-D Hall probes installed at the steel-air interfaces in the gaps between the CMS yoke parts. The readout system of the flux loop-induced voltages is substantially improved during the LHC long shutdown and allows now to measure the small voltages of the order of 20 mV with the sampling rate of 4 Hz.

2 The CMS Magnet Model Description

The CMS magnet model for the upgraded detector is presented in Fig. 1. The central part of the model comprises the four coil layers of the superconductor and the full magnet yoke that consists of five barrel wheels of the 13.99 m inscribed outer diameter and 2.536 m width, two nose disks of 5.26 m diameter on each side of the coil, three large end-cap disks of the 13.91 m inscribed outer diameter on each side of the magnet, two small end-cap disks of 5 m diameter, and two additional 0.125-m-thick end-cap disks of the 13.91 m inscribed outer diameter mounted around these small disks.

The total length of the central part is 21.61 m. On both sides of the central part, the hadronic forward calorimeter

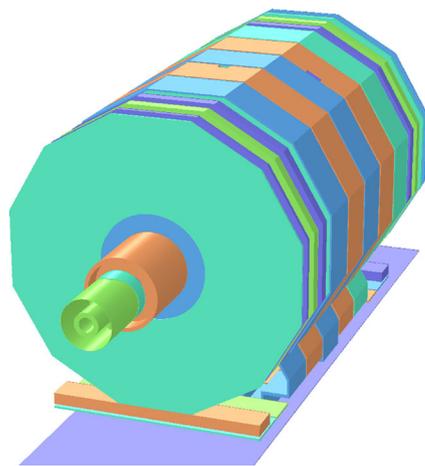


Fig. 1 Three-dimensional model of the CMS magnetic system

absorbers and shields, the steel collars and rotating shields of the beam pipe are included into the model. The 40-mm-thick steel floor of the experimental underground cavern has the length of 36.4 m and the width of 9.9 m.

Each barrel wheel except of the central one has three layers of steel connected with brackets. The central barrel wheel comprises the fourth most inner layer, tail catcher, that is made of steel and turned by 5° 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 the horizontal plane toward the LHC center, the Y-axis is upward, and the Z-axis coincides with the superconducting coil axis and has the same direction as the positive axial component of the magnetic flux density.

The model comprises 21 conductors, the barrel feet, and the end-cap disk carts and contains 7,111,713 nodes of the finite element mesh.

The dimensions of the yoke parts and the superconducting coil modules are described elsewhere [17]. The operational current of the CMS superconducting coil is 18.164 kA.

3 Comparison of the Measured and Calculated Magnetic Flux Density

The measurements used for the comparisons were obtained in the CMS magnet ramp down from 3.81 to 1 T central field with the current ramp down speed of 1.5 A/s

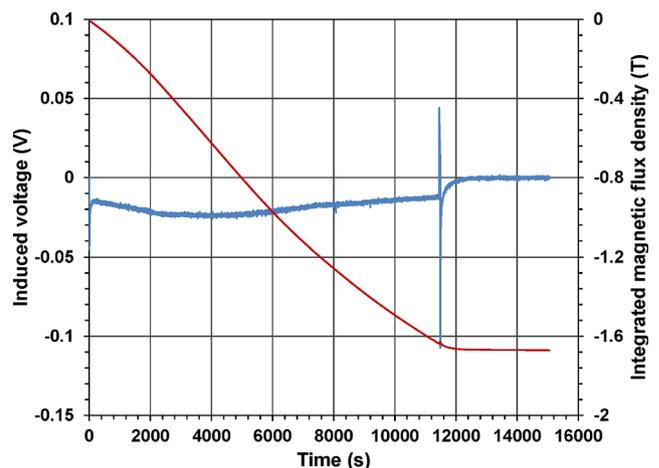
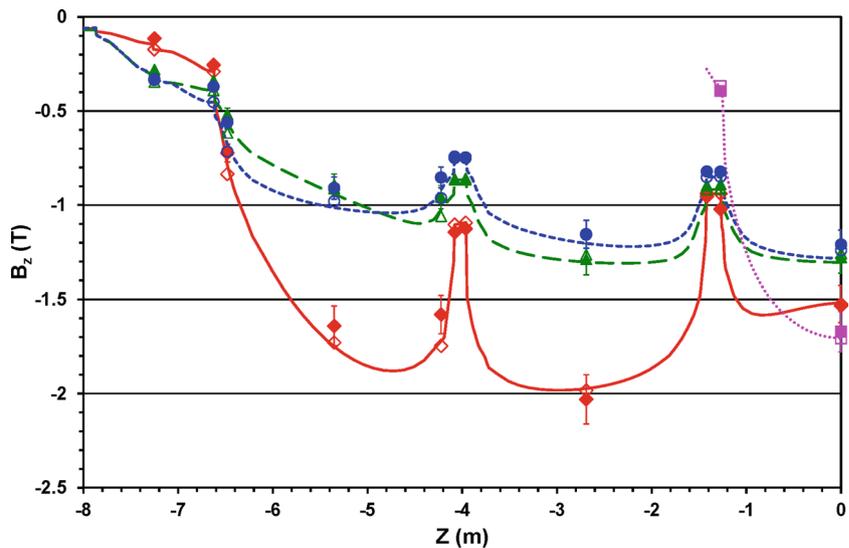


Fig. 2 The induced voltage (*left scale, noisy curve*) and the integrated average magnetic flux density (*right scale, smooth curve*) in the tail catcher block cross section at $Z = 0$ m and at the operational current of 18.164 kA. The rapid maximum and minimum voltages at 11,445 s correspond to the transition from the standard discharge to the fast discharge of the magnet

Fig. 3 Axial magnetic flux density measured (filled markers) and calculated (open markers) in the tail catcher (squares) and the first (rhombs), second (triangles), and third (circles) barrel layers vs. the Z-coordinate at the operational current of 18.164 kA. The lines represent the calculated values along the Hall sensor locations at the positive X-coordinates and at the Y-coordinates of -3.958 m (small dotted line), -4.805 m (solid line), -5.66 m (dashed line), and -6.685 m (dotted line), corresponded to the tail catcher and the first, second, and third barrel layer blocks



and a subsequent fast dump of the current to zero on July 17 and 18, 2015. The measurements of the voltages with maximum amplitudes of 20–200 mV induced in the flux loops were performed during 15,000–17,000 s. The flux loop measurements are complemented with measuring the magnetic flux density with the 3-D Hall sensors installed between the barrel wheels and on the first end-cap disks at Z-coordinates of 1.273, -1.418, -3.964, -4.079, -6.625, and -7.251 m. The sensors are aligned in the rows at the Y-coordinates of -3.958, -4.805, -5.66, and -6.685 [10]. The average magnetic flux density in steel was reconstructed by the off-line integration of the voltages [16] as shown in Fig. 2.

In Figs. 3, 4, and 5, the measured values of the magnetic flux density vs. Z- and Y-coordinates are displayed

and compared with the calculated field values obtained with the CMS magnetic system model at the operational current of 18.164 kA.

The comparison gives the differences between the calculated and measured values of the magnetic flux density in the flux loop cross sections as follows: $6.96 \pm 8.6 \%$ in the barrel wheels and $-1.37 \pm 3.29 \%$ in the end-cap disks. The error bars of the magnetic flux density measured with the flux loops are of $\pm 6.44 \%$ and aroused from the errors in the knowledge of the flux loop geometries. The difference between the calculated and measured magnetic flux densities in the Hall sensor locations is $4.32 \pm 7.12 \%$ at negative X-coordinates and $3.77 \pm 9.0 \%$ at positive X-coordinates. The error bars of the 3-D Hall sensor measurements are $\pm 0.012 \pm 0.005$ mT.

Fig. 4 Axial magnetic flux density measured (filled markers) and calculated (open markers) in the first (rhombs), second (triangles), and third (circles) barrel layers vs. the Z-coordinate at the operational current of 18.164 kA. The lines represent the calculated values along the Hall sensor locations at the negative X-coordinates and at the Y-coordinates of -4.805 m (solid line), -5.66 m (dashed line), and -6.685 m (dotted line), corresponded to the first, second, and third barrel layer blocks

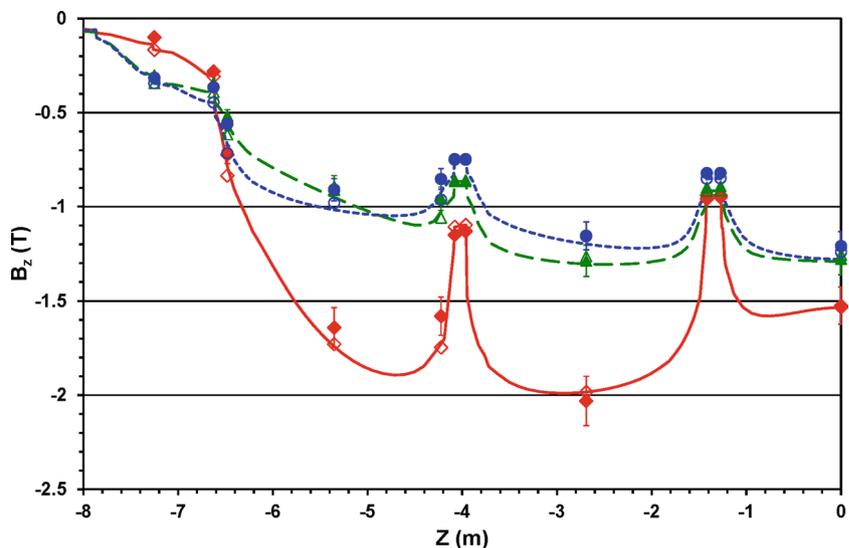
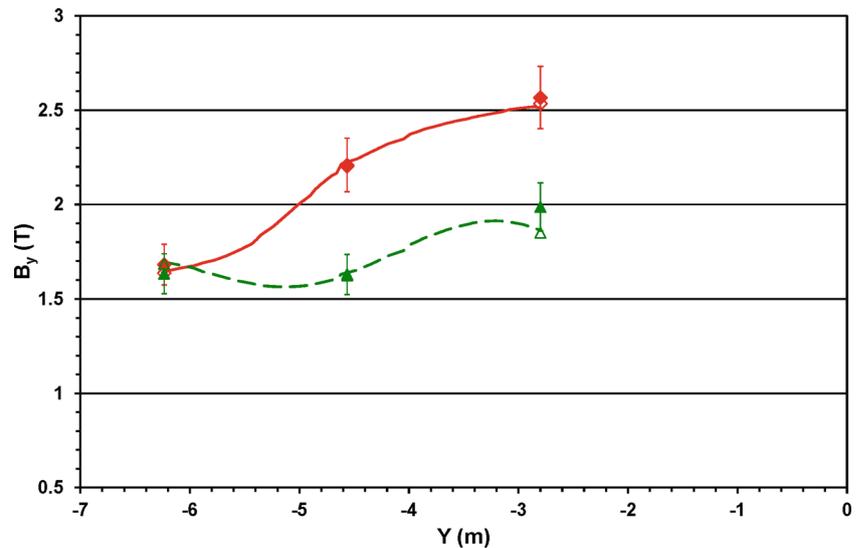


Fig. 5 Axial magnetic flux density measured (*filled markers*) and calculated (*open markers*) in the first (*rhombs*) and second (*triangles*) end-cap disks vs. the Y -coordinate at the operational current of 18.164 kA. The *lines* represent the calculated values in the middle planes of the end-cap disks



4 Conclusions

The first attempt of measuring the magnetic flux density in the steel blocks of the CMS magnet flux return yoke is made using the flux loop technique and the standard magnet discharge with the current ramp down speed of 1.5 A/s. Caused by very small maximum amplitudes of the voltages induced in the flux loops during the standard magnet discharge, the averaged precision of the present measurements is worse than the averaged accuracy of the measurements performed using the CMS magnet fast discharges [10] but still allows to confirm the correctness of the CMS magnetic flux description done with the CMS magnetic system model.

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