*Article*

# Measuring the Magnetic Flux Density with Flux Loops and Hall Probes in the CMS Magnet Flux Return Yoke

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**Abstract:** The direct measurements of the magnetic flux density in steel blocks within Compact Muon Solenoid (CMS) magnet yoke are performed with 22 flux loops installed in selected regions of the yoke. The 10,000-ton CMS magnet flux return yoke encloses a 4 T superconducting solenoid with a 6-m-diameter by 12.5-m-length free bore and consists of five dodecagonal three-layered barrel wheels and four end-cap disks at each end. The yoke steel blocks, mostly up to 620 mm thick, serve as the absorber plates of the muon detection system. A TOSCA 3-D model of the CMS magnet has been developed to describe the magnetic field everywhere outside of the tracking volume which was measured with a field-mapping machine. In the present study, for the first time, the reliable reconstruction of the magnetic flux density in the steel blocks of the yoke is performed using the CMS magnet standard discharges from the operational magnet current of 18.164 kA. To provide this reconstruction, the voltages induced in the flux loops (with amplitudes of 20–250 mV) have been measured with six 16-bit DAQ modules and integrated offline over time. The results of the flux loop measurements during three magnet ramp downs are presented and discussed.

**Keywords:** electromagnetic modeling; flux loops; Hall effect devices; magnetic field measurement; magnetic flux density; measurement techniques; superconducting magnets

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## 1. Introduction

The principal difficulty in large magnetic systems which have an extensive flux return yoke [1,2] within the muon detector is to characterize the magnetic flux distribution in the yoke steel blocks. Continuous measurements of the magnetic flux density there are not possible and the usual practice is to use software modelling of the magnetic system with special three-dimensional (3-D) computer programs [3,4]. Thus, the magnetic flux density in the central part of the Compact Muon Solenoid (CMS) detector, where the tracker and electromagnetic calorimeter are located, was measured with a precision of $7\times10^{-4}$ with a field-mapping machine [5] at the time when both detectors were not installed, and the magnetic flux everywhere outside of this measured volume was characterized by a 3-D magnetic field model calculated with the program TOSCA [6] from Cobham CTS Limited. This model reproduced the magnetic flux density distribution measured with the field-mapping machine inside the CMS coil to within 0.1% [7]. To verify the magnetic flux distribution calculated in the yoke steel blocks, direct measurements of the magnetic flux density in the selected regions of the yoke were performed during the CMS magnet test in 2006 when four “fast” discharges of the CMS coil (190 s time-constant) were triggered manually to test the magnet protection system. These discharges were

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used to induce voltages with amplitudes of 2–5 V in 22 flux loops wound around the yoke blocks in special grooves, 30 mm wide and 12–13 mm deep. The loops have 7–10 turns of 45-wire flat ribbon cable and the cross-sections of areas enclosed by the flux loops vary from 0.3 to 1.59 $m^2$ on the yoke barrel wheels and from 0.5 to 1.12 $m^2$ on the yoke end-cap disks [8]. An integration technique [9] was developed to reconstruct the average initial magnetic flux density in the cross-sections of the steel blocks at full magnet excitation. The comparisons of the magnetic flux densities measured with the flux loops during the fast CMS coil discharges and the magnetic field values computed with the CMS magnet model are presented elsewhere [8,10]. No fast discharge of the CMS magnet from its operational current of 18.164 kA was performed that time.

## 2. Materials and Methods

During the Large Hadron Collider (LHC) long shutdown of 2013/2014 the read-out system of the flux loop voltages was upgraded to replace the 12-bit DAQ modules from Measurement Computing with new 16-bit USB-1608G modules from the same manufacturer. This allowed measurements of voltages of smaller amplitudes with better precision of 0.15 mV that gives 0.75 % at the amplitude of 20 mV. The DAQ modules were attached by USB cables to two network-enabled AnywhereUSB®/5 hubs connected to the DAQ PC through 3Com® OfficeConnect® Dual Speed Switch 5 and a 100 m optical fiber cable with two Magnum CS14H-12VDC Convertor Switches. These modifications permitted measurement of the magnetic flux density in the steel blocks using standard magnet ramp ups and ramp downs with a current discharge rate as low as 1–1.5 A/s. To improve a precision of the flux loop measurements, the total areas covered by the flux loops have been calculated on the basis of each individual wire turn position and vary from 122 to 642 $m^2$, that reduced a systematic error arising from the flux loop conductor arrangement to ±4.89 % on average.

The CMS magnet model used for the magnetic field map preparation and for the comparisons with the measurements was modified to include all the ferromagnetic parts beyond the central magnet yoke as well as the electrical current leads for the solenoid coil as shown in Figure 1.

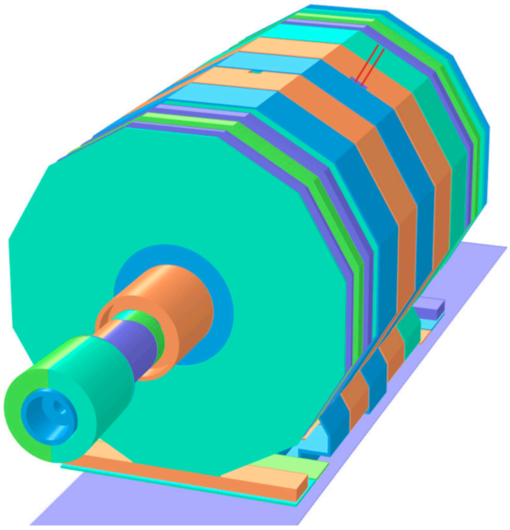

**Figure 1.** CMS magnet 3-D model computed with the program TOSCA at the operational current of 18.164 kA. The cylinders downstream the central 14-m-diameter flux return yoke are the forward hadronic calorimeter, collar, beam pipe rotating shielding, and fixed iron nose. The forward part of the model extends to ± 21.89 m in each direction with respect to the coil center. Two electrical current leads supplying the coil with the current of 18.164 kA are visible outside a special chimney.

The coordinate system used in this study corresponds to the CMS reference system where the *X*-axis is aligned in the horizontal plane towards the LHC center, the *Y*-axis is aligned upwards, 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.

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To perform the comparisons with the measurements presented in this study, the magnetic flux density was calculated in the areas where the measuring devices are located on the CMS yoke steel blocks. In addition to the flux loops, the magnetic flux density was also measured with the 3-D Hall sensors installed between the barrel wheels and on the first end-cap disk at the axial *Z*-coordinates of 1.273, –1.418, –3.964, –4.079, –6.625, and –7.251 m. The sensors are aligned in rows at the vertical *Y*-coordinates of –3.958, –4.805, –5.66, and –6.685 m [10] on two sides of the magnet yoke: the *near* side towards the LHC center (positive *X*-coordinates), and the *far* side opposite to the LHC center (negative *X*-coordinates). In the present analysis, the 3-D Hall sensors installed on the inner surfaces of both nose disks inside the coil were also used.

The magnetic flux density distribution in the CMS vertical plane, as well as the layout of the measuring devices used in this study, are shown in Figure 2. The coil, the three barrel wheels, the nose disk, the first and second end-cap disks with the carts and keels, as well as the experimental cavern steel floor of 40 mm thick are visible.

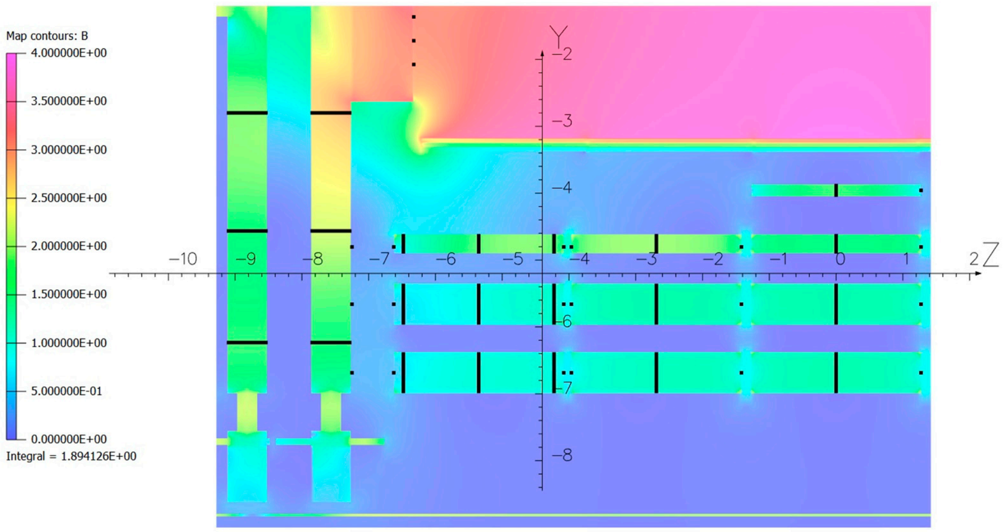



**Figure 2.** The magnetic flux density distribution in the vertical plane of the area where the 22 flux loops are located. The scale is from zero to 4 T with a unit of 0.5 T. The black lines display the flux loop cross-sections. The black squares denote the projections of the 3-D Hall probe positions to the vertical plane.

To cross check the model, the comparisons of the magnetic flux density calculated and measured with four NMR-probes and four 3-D Hall sensors installed inside the CMS coil inner volume were done at the CMS coil operational current of 18.164 kA. Two NMR-probes are located near the coil middle plane at the *Z*-coordinates of ±0.006 m and radii of 2.9148 m; another two probes are installed on the CMS tracker faces at the *Z*-coordinates of –2.835 and +2.831 m and radii of 0.651 m. Four 3-D Hall sensors are located on the CMS tracker faces at the *Z*-coordinates of –2.899 and +2.895 m and radii of 0.959 m. The averaged precision of the NMR-probe measurements was (5.2 ± 1.3) $\times 10^{-5}$, the same of the 3-D Hall sensors was (3.5 ± 0.5) $\times 10^{-5}$. The averaged relative differences between the calculated and measured values of the magnetic flux density were (–5.6 ± 1.7) $\times 10^{-4}$ at the NMR-probe locations, and (–2.4 ± 4.0) $\times 10^{-4}$ at the 3-D Hall sensor locations, that indicates a perfect description of the magnetic flux distribution with the CMS magnet model in the CMS coil inner volume.

## 3. Results

The measurements used for the present comparisons were obtained in three CMS magnet standard discharges from a current of 18.164 kA to zero, carried out in 2015 and 2016 as shown in Figure 3.

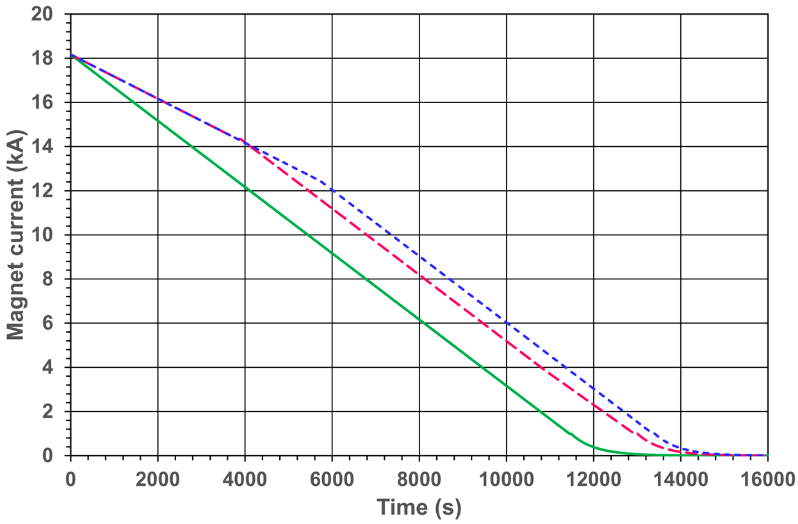
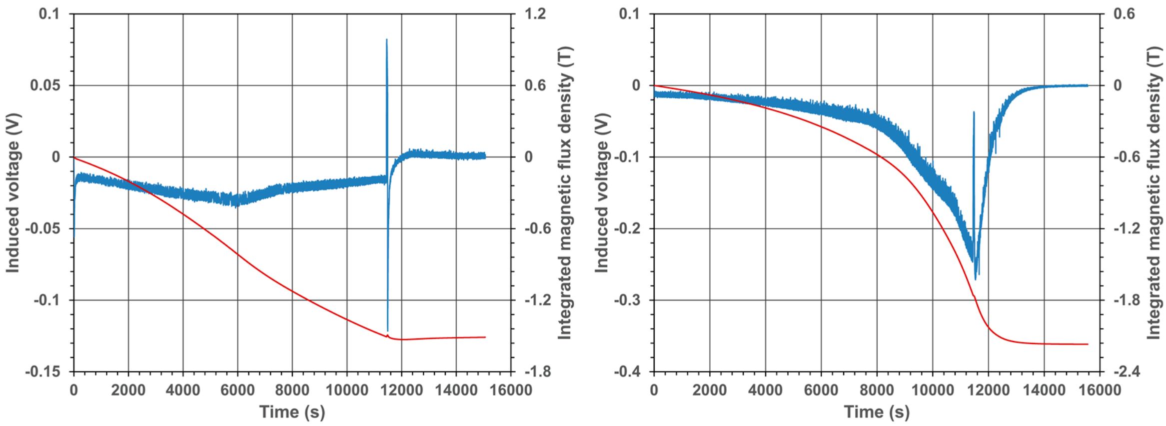



**Figure 3.** CMS magnet current standard discharges from 18.164 kA to zero made on July 17–18, 2015 (*smooth line*), September 21–22, 2015 (*dashed line*), and September 10, 2016 (*small dashed line*).

The first discharge, on July 17–18, 2015, was made with a constant current ramp down rate of 1.5 A/s to a current of 1 kA, and after a pause of 42 s, the fast dump of the magnet was triggered manually to end the discharge. The measurements of the voltages induced in the flux loops (with maximum amplitudes of 20–250 mV) were integrated over 15061.5 s in the flux loops located on the barrel wheels and over 15561.5 s in the flux loops located on the end-cap disks. The preliminary results obtained in this particular magnet ramp down were published elsewhere [11].

The typical induced voltages in the first magnet ramp down, together with the integrated average magnetic flux densities, are shown in Figure. 4. The rapid maximum and minimum voltage at 11445 s corresponds to the pause in the ramp down at a current of 1 kA, and the following transition from the standard ramp down to the fast discharge of the magnet on the external resistor.




(**a**) (**b**)

**Figure 4.** The induced voltage (*left scales, noisy curves*) and the integrated average magnetic flux density (*right scales, smooth curves*) in the cross-section: (**a**) At $Z$ = 0 m of the first layer block of the central barrel wheel; (**b**) At $Y$ = –4.565 m of the first end-cap disk block. The rapid maximum and minimum voltages at 11445 s correspond to the short pause for 42 s in the magnet ramp down at the current of 1 kA, and the subsequent transition from the standard discharge to the fast discharge of the magnet.

The second magnet discharge, on September 21–22, 2015, was performed with two constant ramp down rates: 1 A/s to a current of 14.34 kA, and 1.5 A/s to a current of 1 kA.

The third magnet discharge, on September 10, 2016, was similar, but the current at which the rate transitioned from 1 A/s to 1.5 A/s was 12.48 kA. In both these magnet ramp downs the fast

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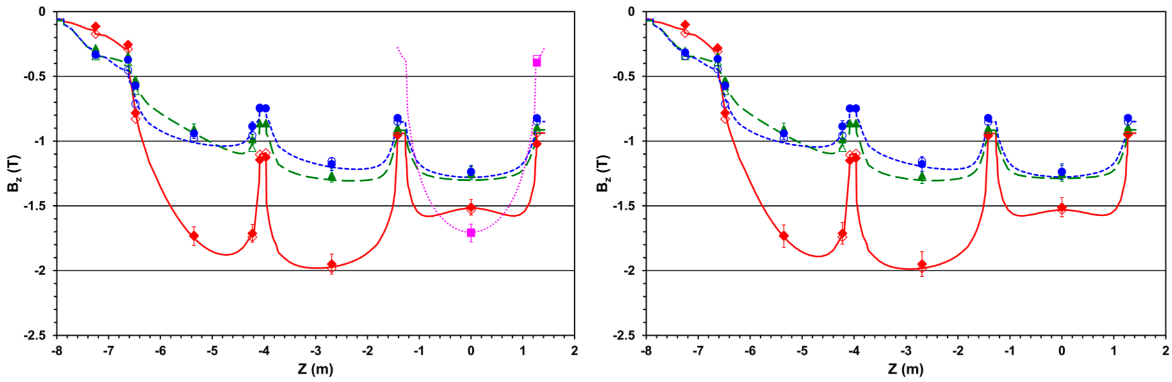
discharges were triggered from a current of 1 kA, and the offline integration of the induced voltages was performed over 17000 s.

In Figures 5 and 6, the measured values of the magnetic flux density vs. *Z*- and *Y*-coordinates are displayed and compared with the field values computed by the CMS model at the operational current of 18.164 kA.




(**a**) (**b**)

**Figure 5.** Axial magnetic flux density measured (*filled markers*) and modelled (*open markers*) in the tail catcher (*squares*) and the first (*diamonds*), second (*triangles*), and third (*circles*) barrel layers vs. the *Z*-coordinate. The lines represent the calculated values along the 3-D Hall sensor locations: (**a**) At the *near* side of the yoke and the *Y*-coordinates of −3.958 m (*dotted line*), −4.805 m (*solid line*), −5.66 m (*dashed line*), and −6.685 m (*small dashed line*).; (**b**) At the *far* side of the yoke and the *Y*-coordinates of −4.805 m (*solid line*), −5.66 m (*dashed line*), and−6.685 m (*small dashed line*).

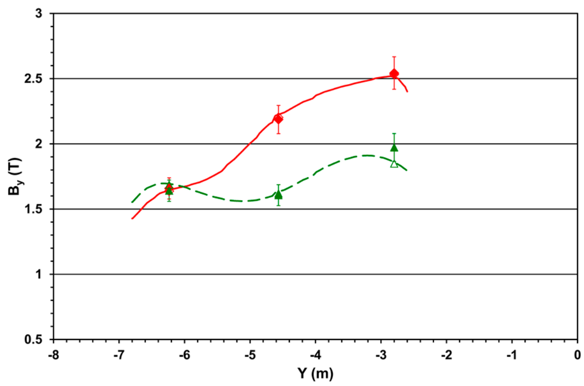



**Figure 6.** Radial magnetic flux density measured (*filled markers*) and modelled (*open markers*) in the first (*diamonds*) and second (*triangles*) end-cap disks vs. the *Y*-coordinate. The lines represent the calculated values in the middle planes of the end-cap disks.

These comparisons give the following differences between the modelled and measured values of the magnetic flux density in the flux loop cross-sections: 4.32 ± 7.05 % in the barrel wheels and –0.61 ± 3.07 % in the end-cap disks. The error bars of the magnetic flux density measured with the flux loops include the standard deviation in the set of three measurements (9.3 ± 6.3 mT or 0.71 ± 0.55 % on average) and a systematic error of ±4.89 % arising from the flux loop conductor arrangement. The difference between the modelled and measured magnetic flux density in the 3-D Hall sensor locations is 3 ± 7 %. The error bars of the 3-D Hall sensor measurements are ± (0.017±0.011) mT.

We have revised as well the comparisons of the calculated values of the magnetic flux density in the yoke steel blocks with the measured values obtained in the 2006 measurement champagne [10]. The differences between the calculations done with the latest CMS magnet model and the measurements are as follows: -1.20 ± 7.66 % in the barrel wheels and −2.33 ± 4.47 % in the end-cap disks at a maximum current of 17.55 kA; 0.62 ± 7.34 % in the barrel wheels and −1.12 ± 4.70 % in the end-cap disks at a maximum current of 19.14 kA. This is compatible with the latest measurements.

## 4. Discussion

The flux loop measurements of the magnetic flux density in steel blocks of the CMS magnet yoke were extremely difficult. The only one attempt was made in the year of 2006 when the detector was not in the full configuration. To repeat the fast discharge of the magnet current when detector has been delivered and tested in the underground experimental cavern was very unfavorable for the detector electronics. Integration of the voltages induced in the flux loops during the standard magnet ramp ups and ramp downs gave too large errors because of reading the very small voltages with the 12-bit DAQ modules. Thus, an upgrade of the readout electronics, revising the flux loop area description, and ability to use the standard ramp ups and ramp downs of the CMS magnet several times a year brought a real progress into the measurements of the magnetic flux density in steel. A stability of the measurements has allowed confirming the correctness of the CMS magnetic field description performed with the CMS magnet model calculated with the program TOSCA.

## 5. Conclusions

For the first time, reliable measurements of the magnetic flux density in the steel blocks of the CMS magnet flux return yoke have been made using the flux loop technique and standard magnet discharges from an operational current of 18.164 kA to zero with a current ramp down rate of 1.0–1.5 A/s. The precision of the measurements is similar to the results obtained in 2006, which used the fast discharges of the magnet from similar current values. These new measurements confirm that the new DAQ system is able to monitor the magnetic flux density in the CMS yoke during any standard magnet ramp up and ramp down as well as the latest CMS magnet model provide us with reliable magnetic flux density values across all the CMS detector volume.

**Author Contributions:** B.C. and V.K. are the main contributors and performed the measurements and the analysis; B.C., V.K., A.B., A.G., H.G., A.H, and R.L. contributed to the flux loops design and performance; V.K., N.A., and M.M., contributed to the modelling of the CMS magnetic field.

**Conflicts of Interest:** The authors declare no conflict of interest.

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