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Measuring the Magnetic Field in the CMS Steel Yoke Elements

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***Abstract*—Flux loops and Hall probes are being installed on selected segments of the steel flux return of the 4 T solenoid of the Compact Muon Solenoid (CMS) detector under construction at CERN (European Center for Nuclear Research). This steel also serves as part of the muon detection system of CMS and accurate characterization of the magnetic flux density in the steel as elsewhere in the detector is required. Voltages induced in the flux loops during fast discharge of the solenoid will be sampled and integrated to measure the change in average flux density in the steel during the discharge. Hall probes mounted on the surface of the steel segments will provide information about the fields internal and external to the steel. In the laboratory work reported herein small iron discs with flux loops on their peripheries and hall probes on their flat surfaces are magnetized between the pole tips of a laboratory standard magnet and controlled power supply. The voltages induced in the flux loops during charging and discharging of the magnet are integrated and compared with the hall probes which sample the fields immediately external to the discs. The experimental work reported here will provide interpretation of the flux coil and hall probe measurements from the CMS magnet when it is commissioned in 2005.**

***Index Terms*— flux loop, Hall probe, magnetic field, steel yoke**

I. INTRODUCTION

THE CMS experiment is a general-purpose detector designed to run at the highest luminosity at the CERN LHC (Large Hadron Collider) [1]. Distinctive features of the CMS detector include a 4 T solenoid coupled with a multilayer muon system, a fully active scintillating-crystal electro-magnetic calorimeter, a tile hadronic calorimeter, and a powerful inner tracking system.

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A three-dimensional calculation [2] of the magnetic field everywhere in the CMS detector has been made with the program TOSCA [3], and to substantiate the results of this calculation, flux loops and hall probes have been installed on selected segments of the CMS steel to provide direct measurements of the flux densities in these locations in an effort to achieve overall accuracy of the field values in the steel of a few percent. The TOSCA calculation relies on the use of "averaged" permeability values measured from coupons taken from the steel plates from which the CMS flux return yoke was fabricated, and it necessarily simplifies and symmetrizes the detector geometry to satisfy computer storage limitations and calculation times.

During the commissioning of the 4T superconducting solenoid, one or more fast discharges of the solenoid will be made to test the magnet protection system. During these discharges measurable voltages will be induced in the flux loops installed on the steel blocks which will permit the measurement of the magnetic flux density changes in the steel during the discharge [4].

The laboratory program described here has been undertaken to help interpret the results of the flux loop data and hall probes of the CMS magnet system.

II. FLUX LOOPS AND THE CMS FAST DISCHARGE

The CMS solenoid will be charged at one polarity from zero current to a fixed current (approximately 20 kA) which results in 4.0 T in the tracking volume of the detector. The charge time is approximately five hours and the normal discharge time is of like duration. An emergency discharge, required by the protection system of the magnet, is provided which discharges the system with a 190 second time constant during which time the coil also quenches due to eddy current heating in the coil outer support cylinder. No provision is made to charge the magnet at opposite polarity.

Despite the sizes of the steel blocks encompassed by the flux loops, normal charging and discharging will not induce readily measured voltages in the loops. Emergency discharges however are sufficiently rapid to make the measurement of flux loop voltages practical. The protection system will be tested during the commissioning of the magnet system so an opportunity exists to measure magnetic flux changes in the CMS steel yoke elements by sampling and integrating these voltages. The rapid discharge of the CMS solenoid into a fixed resistor, which takes into account quenching of the coil, is shown in Fig. 1.

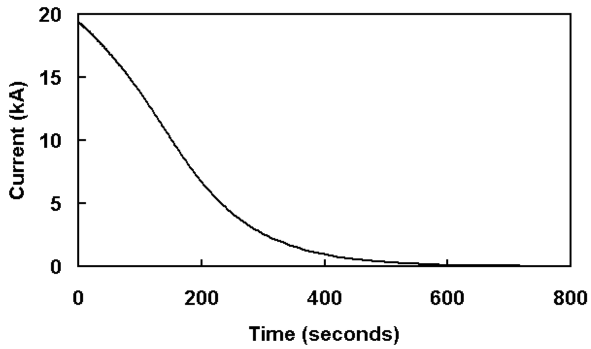

Fig. 1. CMS fast discharge into a fixed resistor. Quenching is induced in the magnet so the decay is not a simple exponential.

Calculations of the flux densities in representative steel blocks at 9 successive currents during the discharge (i.e. at times after the beginning of the discharge of 0, 50, 100, 125, 151, 176, 200, 251, and 306 seconds) have been made and the average voltages induced in flux loops around these blocks is calculated from the relation $V = \Delta\Phi/\Delta t$. Representative voltages are shown in Fig. 2.

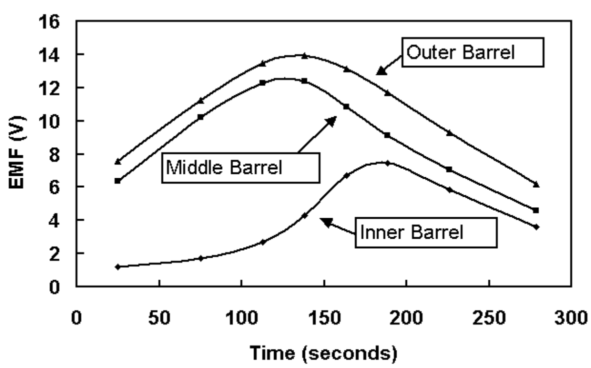

Fig 2. EMF per one-turn loop at axial center of barrel steel slabs at different radii. Voltages induced in end-cap steel segments are of similar magnitude.

The CMS flux loops each consist of a 405-turn coil (a 9-turn 45-conductor ribbon cable re-connected in offset to yield 405 turns in series) embedded in a shallow groove machined into the surfaces of the steel plate that is to be sampled.

It is the goal of this study to determine if these voltages can be integrated over the entire discharge with sufficient accuracy to provide a measurement of the initial average flux density in the steel to a few percent uncertainty. As noted, it is not possible to cycle the CMS steel around a full hysterisis loop to measure its remanent field directly, nor even to a predetermined negative current that results in a reasonable degaussing of the steel when the current returns to zero. Hall probes mounted on the surface will provide information about the remanent fields in the steel. A laboratory program reported herein has been undertaken to determine the sensitivity and accuracy of this approach.

III. EXPERIMENTAL APPROACH

A. Voltage Measuring System

A commercial precision voltage sampling data acquisition system [6] with fast analogue to digital conversion (ADC) was selected for the measurement of voltages from the flux coil. The differential inputs of the sampling system were referenced to ground through 100 K resistors, and the system was operated with National Instrument's Labview© software running on the same PC that controlled the magnet. The use of voltage sampling with offline numerical integration avoids the need for highly stable electronic integrators otherwise necessary to integrate the flux coil voltages during the very long times of the CMS discharge.

B. Flux Coil

A 994-turn model flux coil approximately 13.7 cm in diameter was wound on a non-metallic coil former and connected to the sampling circuitry in differential mode to reject common-mode noise. The flux coil has an open center in which flat discs of steel or aluminum 13.5 cm in diameter can be inserted. The diameter of the flux coil was chosen to encompass only the flat portion of the 15 cm diameter pole tips of an electromagnet, and the number of turns and charge/discharge rates were selected to yield voltages that approximate those expected from the flux loops of the CMS magnet. During intital hookup the flux coil and DAQ generated noise signals below 1 mV in a laboratory ambient environment and with only air in its core, the flux coil was sensitive at the 1-2 mV level to the nearby motion of a small permanent magnet.

C. External Magnetic Field

A laboratory standard electromagnet [7] was used to vary the flux in the flux coil. Typically, when a CMS steel disc was inserted in the flux coil, the pole tips of the magnet were adjusted to leave narrow air gaps 3.18 mm thick on either side of the steel adjacent to the magnet pole tips. Hall probes [8] were inserted in the gaps to measure the normal field at the surfaces of the steel being studied. The electromagnet was charged and discharged at varying rates under software control and the voltages from the flux coil recorded and integrated off line to measure the flux changes through the coil.

D. Materials Studied

Discs machined from the same steel ingots as were used for the CMS barrel and end yokes were studied, as was a disc machined from ordinary cold-rolled construction steel, and a disc machined from 5083 aluminum. One iron disc was quartered into segments to evaluate the effects of eddy currents.

IV. MODELING THE ELECTROMAGNET

A TOSCA model (Fig. 3) for the laboratory standard magnet was prepared to guide the interpretation of the data obtained from the flux coil.

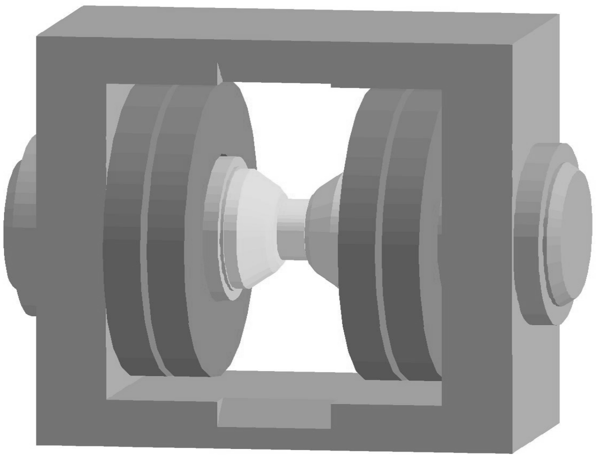

Fig. 3. TOSCA 3D model of the electromagnet. The flux coil (not shown) encircles the disc shown suspended between the poles of the magnet.

The TOSCA model predicted a central axial magnetic flux density of 3.00 T when the hall probes in the air gaps on either side of the steel disc averaged 2.94 T. The two hall probes typically agreed to within a few tenths mT at 2.5 T but varied by approximately 10mT at 3 T. This variation is attributed to the fact that they were calibrated only to 2.2 T some years before use in this experiment. The remaining discrepancy between TOSCA and the Hall probes is attributed to the necessarily imprecise assumptions made to create the magnet model (e.g. the magnet pole tips were assigned the same B-H properties as one of the steel samples studied). When TOSCA calculations were compared to Hall probe measurements, the TOSCA values were scaled by 0.9799.

V. DATA FROM THE MODEL FLUX COIL

With a steel disc 38.1 mm thick (of CMS yoke steel) inserted in the flux coil, the magnet was charged at a constant rate (2.5 Amperes/sec) to 320 Amperes as seen in Fig. 4a.

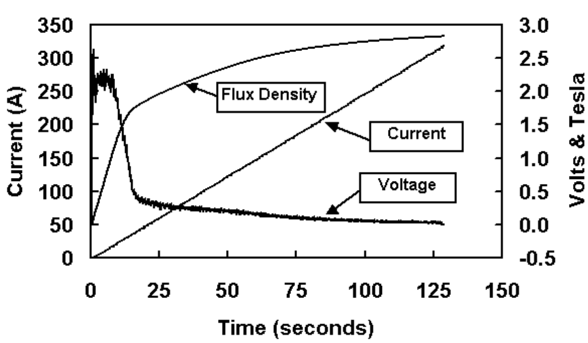

Fig. 4 a. Charging the electromagnet to 320 Amperes

The linear rise of the current in the electromagnet is shown in Figure 4a, and the voltage measured on the flux coil is seen as the ragged curve in Fig 4a. The voltage shows an early rapid decrease to more than 2.5 volts due to the initial highly non-linear magnetization of the magnet pole tips and steel disc, followed by a gradual decrease to zero as the magnet current reaches maximum value. During the charging the voltage on the coil is sampled at 50 ms intervals and logged by the PC. The voltage integral (Volt·seconds) is calculated offline merely by summing at each current step the average of the voltage on the coil multiplied by the duration of the step. The integral is normalized by the area of the flux coil and the number of turns to provide flux density (Tesla) shown in the figure.

A close-up examination of any portion of the chargeup shows the step-wise increase of the magnet current (1 amp every 2.5 seconds with the magnet power supply operating in current-regulate mode), and the corresponding pulsed voltage on the flux coil. The discharging of the CMS magnet will be resistive and hence completely smooth. When the laboratory magnet was charged extremely slowly, so the individual voltage pulses from each current step were spaced many seconds apart, the integral of the voltage was identical to within ~ 1% of the integral obtained when the current varied as rapidly as shown in Fig. 4a. The sampling system is sufficiently precise to integrate step-wise changes without important loss of accuracy.

After a pause, the current was decreased to zero as shown in Fig. 4b at an enhanced rate to provide voltages that simulate the CMS discharge.

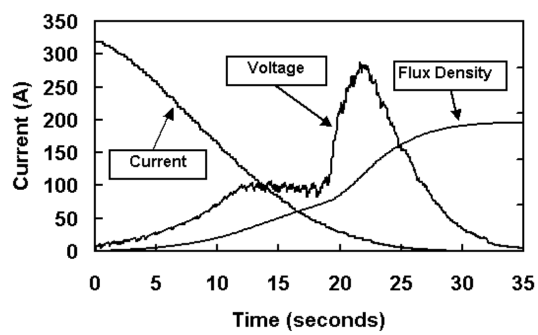

Fig 4b. Discharging the electromagnet in 32 seconds.

The voltage on the flux coil rises later in the discharge due to the non-linear permeability of the steel in the magnet and steel disc, and the voltage on the flux coil remains finite after the magnet current is finally set to zero (at 32 seconds in Fig. 4b). The voltage on the flux coil remains nonzero when the magnet current is set to zero. Instead it decays over time well beyond the end of the discharge as seen in detail in Fig. 5, where the origin of time is put at the point where the magnet current is set to zero. The last two current steps of the discharge are seen at "negative" time in Fig. 5, and the voltage induced in the flux coil pulses noticeably just as the magnet current is set to zero. The flux density (voltage integral) ceases changing measurably only after many tens of seconds have elapsed beyond the end of the discharge.

The decay in Fig. 4b was programmed so the set-to value of the magnet current was reached 0 in 32 seconds. When this decay was slowed to 64, 128, 256, and finally 512 seconds, similar flux coil voltage shapes were observed, but scaled by the ratio of the decay times (for all trials the charge-up rate, 2.5 A/s, was fixed for convenience).

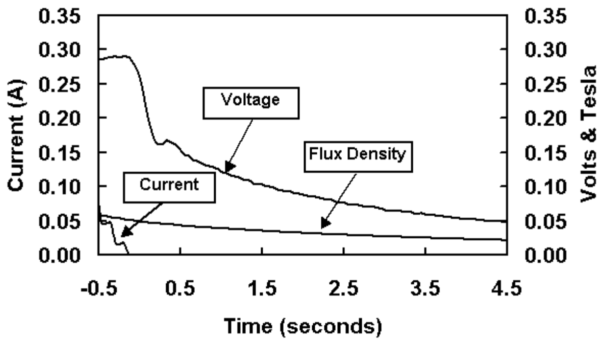

Fig. 5. Detail at end of magnet discharge and beyond

The flux measured by the coil during the series of runs was identical to within 0.5% for all the chargeups. More importantly, the flux measured by the coil during charging corresponded closely to the flux measured by the coil during discharging, *provided the flux coil during discharging was sampled sufficiently long after the magnet current reached zero to integrate the complete "tail" of the voltage on the flux coil seen in Fig. 5*. At the point where the magnet current reaches zero the flux integral is substantially less (depending on the discharge speed) than it ultimately becomes when the voltage on the flux coil finally falls completely to zero.

In Fig. 6 is shown a summary of some of the flux coil charge and discharge studies. Each run consists of a charge-discharge cycle, and the runs were ordered in time. For all the curves except one, a CMS steel disc was inserted in the flux coil. The (black) curve marked with square dots indicates the discharge times for the various runs.

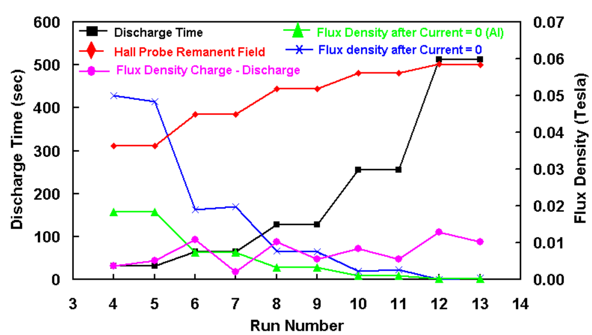

Fig. 6. Some results of the charge/discharge cycling studies. All studies except the one marked with triangles used a CMS steel sample disc in the flux loop. The study marked with triangles used an aluminum disc.

In Fig. 6 the (blue) crosses mark the flux density collected by the coil between the time the discharge ends and 70 seconds later, when the voltage on the coil has reached zero. For the fastest discharge this flux density is nearly 50 mT, falling to essentially zero for the slowest discharges. A similar phenomenon was observed when data from studies with an aluminum disc were done (curve with green triangles). Scaling by the relative thicknesses of the aluminum and steel discs, and the resistivity of aluminum vs. that for steel, one would expect eddy currents in the aluminum to be ~ 5/3 times that in the steel. Clearly, eddy currents in the magnet pole tips also play a significant role in the decay of the flux in the discs under test. The equality of the flux integrals for charging and discharging (~ 0.5%) when sufficient time is allowed for the decay of all eddy current shows that the presence of eddy currents ultimately has little effect on the flux measurements themselves.

VI. HALL PROBE MEASUREMENTS

When CMS steel samples were under study, the pole tips of the magnet were left slightly open to allow the insertion of Hall probes in the resulting air gaps on either side of the steel disc. The Hall probes measured small fields in the gaps at the beginning and end of each charge-discharge cycle. Those at the ends of the cycles are shown in Fig. 6 by the (red) curve marked with diamonds. As can be seen the remanent fields increase more noticeably after fast discharges have been conducted [9].

The Hall probes always indicate a larger flux density at the end of a given charge-up than the flux loop. This excess is seen to be strongly dependent on the discharge rate until it is realized that the flux coil does not measure the remanent field that may be present before the charging begins. When the remanent field at the beginning of each charge-up is added to the flux coil results at the end of the same charge-up the differences between the hall probes and the flux coil is a nearly constant number (76 +/- 1 mT) independent of the nature of the cycle.

VII. CONCLUSIONS

The results of the experimental program indicate that the increase or decrease of flux density in a steel object magnetized by an external source can be measured with good precision using the techniques chosen. The use of hall probes will enable the assessment of the remanent fields in the steel as well as any tendency for these to change as the magnet is cycled at only one polarity.

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[6] National Instrument's DAQ Card 6012®, fully encapsulated on a standard PCMCIA Type II card providing 8 double-ended channels with 16-bit resolution, operating at up to 20 kHz, with absolute accuracy of the order 0.005%. The input impedance of the ADC is of the order of 10 G Ω in parallel with 100 pF.

[7] GMW Model 3474 electromagnet with 15 cm poletips, energized with Danfysik Model 8530 power supply with GPIB interface.

[8] Group III Model 141 and 151 transverse-field probes.

[9] K. Halbach, "Some Eddy Current Effects in Solid Core Magnets", *Nuclear Instruments and Methods* 107 (1973), p. 529-540 (North Holland).