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Tests and Field Map of LHCb Dipole Magnet

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Abstract—**The LHCb experiment at the LHC at CERN is aimed to study CP violation and to measure the rare decays of B-mesons with exceptionally high precision. A 4 Tm dipole magnet is required for particle separation and momentum measurements. The 1600 ton warm magnet with sloping poles was installed and fully commissioned by the end of 2004. It is the first detector magnet of the four LHC experiments to have been aligned and commissioned in its final position. In this paper the magnet installation in the underground cavern of Point 8 and its alignment on the beam line are shortly reviewed. Results of a first magnetic field mapping in the region of the magnet poles and the fringe field in the location of the RICH detectors are presented. The mechanical equipment used for the automatic displacement of the Hall probe array is described together with the precision of the measurements obtained which are compared with TOSCA finite element calculations.**

Index Terms— **Magnetic field measurement, Testing, Detectors, Dipole magnet, Magnetic Devices.**

I. INTRODUCTION

THE LHCb experiment at the Large Hadron Collider (LHC) at CERN is a high luminosity single arm forward spectrometer dedicated to the observation and measurement of CP violation in the decay of B-mesons produced in proton-proton collisions. The experimental set-up is of a fixed-target-like structure, with a dipole magnet that provides charged particle identification and momentum measurement in a large volume of space. The sub-detectors are located forward of the collision point, in an acceptance of ±250 mrad vertical and ±300 mrad horizontal. The required detector acceptance has been obtained by using a prismatic shaped dipole gap of about 20 m^3. The integrated magnetic field is 4 Tm for tracks of 10 m length originating at the interaction point. More details on the design evolution of the magnet project and on the reasons for opting a resistive magnet instead of a superconductive one, can be found in the Magnet Design Report and in papers presented at previous conferences [2]-[3]-[6].

A full description of all sub-detectors used in the experiment can be found in [1]. LHCb will use two Ring Imaging CHerenkov (RICH) detectors to identify particles in the momentum range of 0-100 GeV/c. Large steel boxes around the RICH system downstream of the Interaction Point (IP) are used to channel magnetic flux from the LHCb dipole and providing the magnetic shielding for the Hybrid Photon Detectors (HPDs) which are inside. Therefore the design had to accommodate the contrasting needs for a field level inside the RICH's envelope less than 2 mT and a field as high as possible in the regions between the tracking station, the Vertex Locator, and the Trigger Tracker [5]. To safely operate the RICH with high efficiency it was decided to put large arrays of mu-metal tubes around the HPDs inside the boxes, further attenuating the field. Extended simulations with TOSCA have been carried out to define the boxes geometry, its material and relative positioning [5]. Measurements have shown that the residual field inside shields is acceptable (<1 mT) and that the field in mu-metal shields is not close to saturation (0.7 T).

II. ASSEMBLY AND ALIGNMENT

Due to the restricted access of the 40 t cranes, the magnet had to be assembled outside the beam area, in a temporary position of the underground Experimental Point 8. Plates of laminated low carbon steel (EN-S235JRG2) of 100 mm thickness, having a maximum weight of 25 t, were used to form the identical horizontal bottom and top parts and the two mirror-symmetrical vertical parts (uprights) of the magnet yoke. Design and production of the iron plates was carefully carried out in order to avoid any machining in the underground area while respecting assembly tolerances. At the same time careful design, operation and controls made it possible to avoid a pre-assembly (on the surface or in the pit) and additionally reduced time and cost. The only allowed operation in the pit was the spot weld of the plates in their mounted position to avoid deformation and relative movements during assembly. Specifically, to reach the design tolerances, a controlled pre-stress of 200 t was imposed on each of several M80 tie-rods using a system of SUPERBOLTS® [1] to press up to 27 of the 100 mm iron plates together and make the yoke a solid block. Soft steel strips were used in the mating yoke parts to match unevenness, e.g. between the upper surface of the bottom yoke part and the uprights. The mounting sequence was: horizontal bottom yoke part – vertical uprights – provisional fixation of bottom and upper coils – horizontal upper yoke part – centering and final fixation of coils. The bottom yoke part has been glued

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with non-shrinkable cement and solidly fixed to the carriage by some welded blocks.

The two coils, each made up of 5 triplets as explained in [2], were definitely fixed inside the yoke only at the end of the assembly sequence. Due to the general dimensions and wedge shaping of the poles, a combined method of optical and mechanical surveys had to be used in order to establish with the necessary precision the magnet mechanical axis, and to locate reference marks. Cast Aluminum clamps were used to hold the triplets, and to support and center the coils with respect to the measured mechanical axis of the iron poles with tolerances of some mm. This tolerance is critical because of the computed effect on the magnetic field of coils off-axis relative to the iron: +5 mm off-centering (in all the three directions of space) means an added 3% of field non-homogeneity upon the nominal one.

The completed magnet had to be rolled into its nominal position, several meters away from the assembly location, both in the axial and transversal directions. A special system of motors and endless screws were used. The final precise adjusting and the optical alignment needed to follow the 3.601 mrad slope of the LHC machine and its beam were carried out with hydraulic jigs. The resolution of the alignment's measurements was about 0.2 mm while the magnet could be aligned to its nominal position with a precision of ± 2 mm, which is very good, considering the weight, geometry and dimension of the yoke. About 10 reference marks were optically targeted to reconstruct the 3D yoke position.

As the main stress on the conductor is the thermal one, the design choice was to leave the pancakes of the coils free to slide upon their supports, with only one coil extremity kept fixed against the iron yoke (where electrical and hydraulic terminations are located). Finite element models (TOSCA, ANSYS) have been extensively used to investigate the coils support system with reference to the effect of the electro-magnetic and thermal stresses on the conductor. Even though the analysis was not expected to give an exact prediction, the measured displacement of the coils during magnet operation has matched the predicted value quite well.

III. MAGNET COMMISSIONING

After having precisely adjusted the magnet on the beam position, the electrical and hydraulics connections were completed. The thyristor power converter (950 V, 6500 A) had passed short-circuit tests before being connected to the magnet but it still had to be fine-tuned with the actual L-R load, and this was part of the commissioning activities. The magnet services include the control instrumentation to check pancake temperatures and voltage drops, inlet and outlet water flow, pressure and temperatures. Proximity gauges to measure the movements of the coils during current ramping up and down were incorporated. Pressure test, insulation vs. ground and power supply controls and regulation were carried out. The stand-alone Magnet Control System (MCS) and Magnet Safety System (MSS) were checked and interlocks and set-points were fine tuned. The first current was injected into the magnet in November 2004, and the nominal current of 5.85 kA was reached soon after, representing the first of the 4 LHC detector magnets to be made fully operational on the beam line. The magnet was safely operated for some time at 13% above the nominal current.

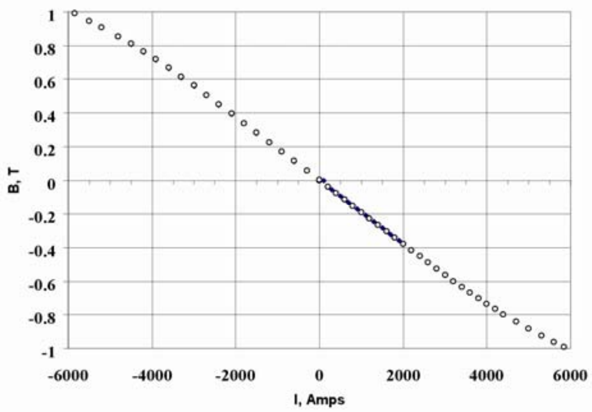

Fig. 1. Measured hysteresis loop. An enlarged view shows that the loop is closed to an accuracy of 0.2%.

Due to the power restrictions during the winter period only a first set of measurements were made in November 2004 with the aim of checking the system for reliability and precision. For reasons of installation activities of the LHC machine and the LHCb detectors during daytime, the magnetic field measurements could only be done at night. Some of the results did not agree with expectations as concerning the precision of the measurements. It was decided to delay the search for any possible flaw in the measurements, mechanics or operation, until the completion of the RICH1 assembly in the upstream position. This came to an end during June 2005. In fact, FEA simulation shows that the RICH1 shielding boxes, due to their closeness to the magnet have a relevant influence on the field at the pole region: a shift of some cm in the axial position of the field maxima was computed due to presence of the boxes.

The second field map, measured during June and July 2005 gave the possibility to fine tune the calibration routines of the Hall probes and there was found a good agreement between the measurements and the expectations. The field in the RICHs boxes, with and without the mu-metal tubes, was measured as well as the fringe field at the several locations in the pit. The main magnet parameters are reported in Table I. Fig.1 shows the measured hysteresis loop. After many cycles of operating the magnet, a long duration test (for almost 30 hours of uninterrupted operation) was carried out in July 2005 and showed the reliable and stable operation of the magnet system.

IV. MAGNETIC MEASUREMENTS SET UP

In order to obtain the necessary high resolution of the charged particle tracks, LHCb needs to know $\int B.dl$ with an uncertainty of a few times 10^{-4} and the position of the B-field peak with a precision of a few mm.

A special measuring machine was designed to enable mapping the LHCb magnetic field with the required precision. The same machine with only few modifications has been recently adapted to carry out the magnetic field mapping of the ALICE dipole, which has an equally complex geometry. To improve data quality and reduce human errors the measurement system has been built with some redundancies. One of these is the possibility to overlap measurements to crosscheck data. A remotely controlled motor system situated outside of the magnet is used to scan through the dipole longitudinal axis. A support holds two adjacent G10 planes each equipped with 30 printed circuit cards distributed over a grid of 80 mm x 80 mm. Every sensor card has mounted on a cube of 4 mm side dimensions three orthogonal and calibrated Hall probes. The support can be placed (manually) orthogonal to the z-axis in the up/down (y-axis) or right/left (x-axis) directions, to allow mapping of different regions. The 3D sensor cards are the result of a joint R&D carried out by CERN and NIKHEF and are calibrated at CERN to a precision of 10^{-4}. To get such a high precision the sensor cards were accurately measured (with NMR) in a constant homogeneous magnetic field B while rotating the cards (which are positioned with a 0.01 mm precision) over two orthogonal axes. The temperature T is also measured to allow taking into account possible effects on the calibration. The Hall-voltage is decomposed in orthogonal functions and the magnetic field parameterized in polynomial coefficients. The calibration process allows corrections for non-linearity, temperatures effects and non-orthogonality. A special calibration machine has been set-up at CERN [4].

While the z movement of the probes support is controlled by the external electrical motor, for reasons of simplicity and cost it was decided to manually operate (the support of) the 60 Hall-cards along the vertical (y) and transversal (x) directions to cover the regions to be mapped. In Fig.2 is shown the mapping machine with its Hall plate supports.

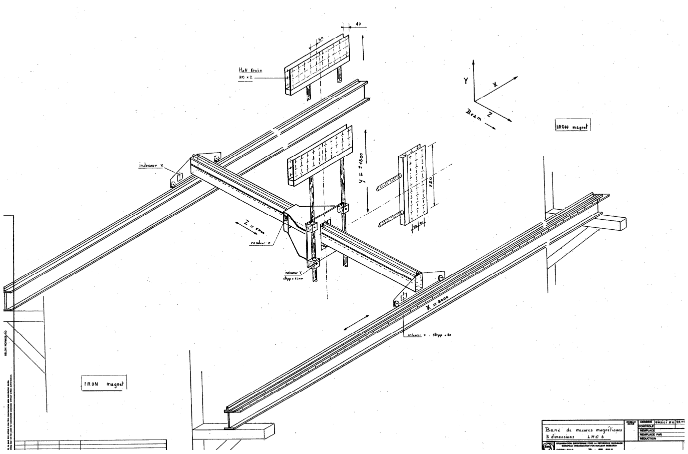

Fig. 2. Magnetic measurement machine.

After being mounted within the LHCb dipole magnet, the elements of the machine had to be aligned along the LHC beam axis: the rails along which the carriage holding the Hall probes moves and the support itself, were aligned with 0.2 mm relative accuracy, and about 1 mm of absolute precision.

V. RESULTS OF FIELD MAPPING

Fig. 3 indicates the measured precision of the measurements. It represents the relative field variation, measured by different probes in two successive repositioning of the machine at the same spatial position. The value of 3 x 10^{-4} includes the mechanical tolerances of the machine. The absolute precision of the measurements is -/+ 0.1 mT over 0 – 1 T range.

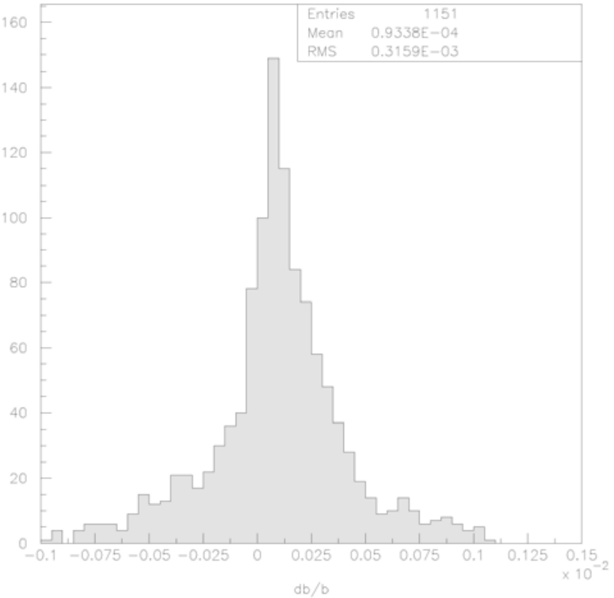

Fig. 3. Precision of the magnetic measurements. The statistics of relative field variations measured repeatedly with different probes at the same spatial position, yields a RMS of 3 .10^{-4}.

Fig. 4 shows the measured field on axis and the TOSCA simulation. There is a very good agreement, with some perceptibly differences only in the upstream region, which is shown enlarged in Fig.5, where the RICH1 is located. In this simulation the iron embedded in the concrete of the reinforced foundation at the upstream region is not included. Indeed it is believed this iron is partially responsible for the differences shown in the graph: successive simulations have demonstrated that iron placed close to the RICH1 lower shield and around it, is able to modify the field shape on axis, as it deviates the magnetic flux. This will not be a concern anyway as in the upstream region the requirements of precision in $\int B.dl$ can be released to few percents without losing spatial resolution of the tracking. It has been found that the field integrals measured on axis, from -0.5 m to 7.9 m and the simulation are matching within 1.5%. Though analysis is still going on, it is believed that the measured field non-homogeneity is well within the expected values.

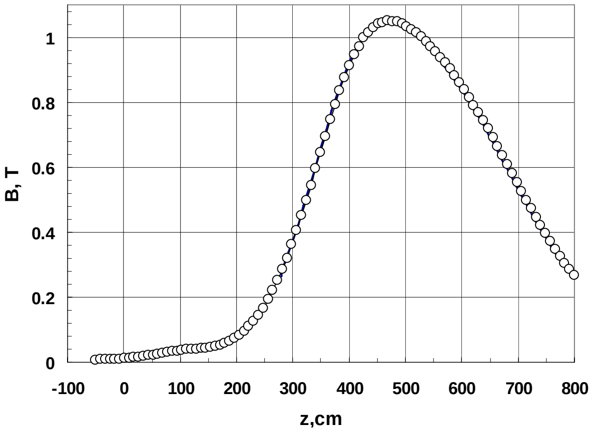

Fig. 4. Measured and computed field on beam axis.

The peak field value, whose position is important for physics reconstruction purposes, has been determined at the nominal current to be 1.046 T. Its position fitted at mm precision from the measurements done, is within 2 cm from the computed expectation, at 4.685 m from the IP.

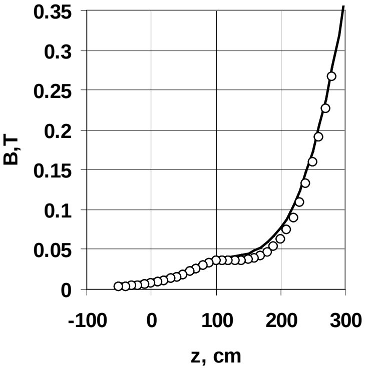

Fig. 5. Measured and computed field on axis in RICH1 region.

Fig. 6 shows the field strength as function of x coordinate, for several z positions inside the acceptance cone. The non-uniformity evaluated from data in this region is well below 1%. The magnet will be operated in both polarities and for physics calibration reason at exactly the same field strength. To understand the effect of magnetic hysteresis we took measurements of both polarities, without current overshoot. It was found that without a de-magnetization cycle, the hysteresis effect produces a remnant field in the order of 1 mT. The LHCb collaboration will decide whether this is acceptable or if degaussing cycles shall be needed every time the magnet changes polarity.

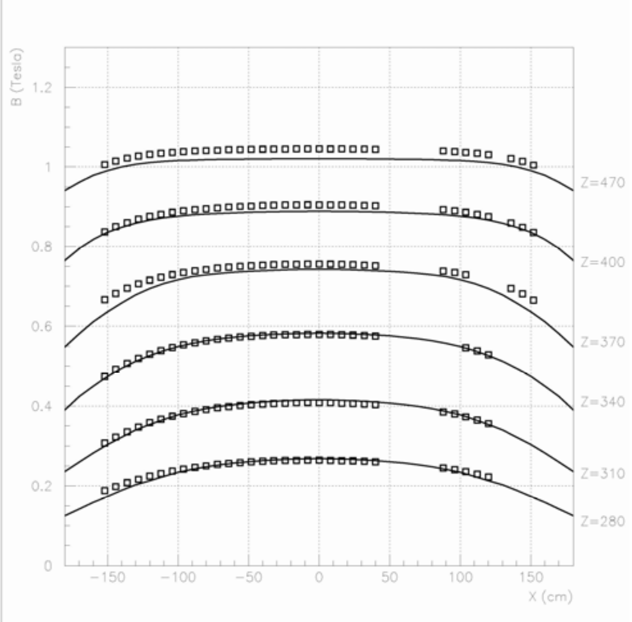

Fig. 6. Measured and computed field strength vs. x, at several z positions.

VI. CONCLUSION

The magnetic measurement of the LHCb dipole, using the especially designed and calibrated 3D B-cards, has paved the way to other similar activities for some of which we are already working on (ALICE dipole, L3 and ATLAS solenoids). Up to now the generally accepted requirements of magnetic measurements for detector magnets have been less demanding than for accelerator magnets. But at LHC detectors will require the knowledge of the magnetic field with very high precision, in the order of 10^{-4} or even better. Simulations have been demonstrated to be sufficiently accurate to reproduce the field into the gap regions, but when such a precision is also required in the large sub-detector volumes, it becomes a cumbersome operation. To replicate the complexity of the experiment, with its precise and large ferromagnetic environment is one of the challenges of the analysis.

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TABLE I
MEASURED MAIN PARAMETERS OF THE LHCB MAGNET

Magnetic Parameters	
Non-uniformity of |B|	≤ ± 1% in planes xy of 1 m^2 from z=3m to z=8 m
∫B dl upstream TT region (0-2.5 m)	0.108 Tm
∫B dl downstream TT region (2.5 – 7.95 m)	3.615 Tm
Max field at HPD's of RICH1	20 G (14 G with mu-metal)
Max field at HPD's of RICH2	9 G
Electric power dissipation	P_e = 4.2 MW
Inductance	L ≈ 1.3 H
Coils and Current	
Nominal / maximum current in conductor	5.85 kA / 6.6 kA
Total resistance (two coils + bus bars)	R = 130 mΩ @ 20 ºC
Total voltage drop (two coils)	U ≈ 730 V
Cooling	
Total water flow	Φ ≈ 150 m^3/h
Water Pressure drop	Δp ≈ 11 bar @ ΔT = 25 °C
Mechanics	
Overall dimensions	H x V x L: 11m x 8 m x 5 m
Total weight	1600 tons

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