Chapter 4

Magnet

4.1 General description

A dipole magnet is used in the LHCb experiment to measure the momentum of charged particles. The measurement covers the forward acceptance of ± 250 mrad vertically and of ± 300 mrad horizontally. The super-conducting magnet originally proposed in the Technical Proposal [1], would have required unacceptably high investment costs and very long construction time. It was replaced by a warm magnet design with saddle-shaped coils in a window-frame yoke with sloping poles in order to match the required detector acceptance. Details on the design of the magnet are given in the Magnet Technical Design Report [23] and in [24, 25]. The design of the magnet with an integrated magnetic field of 4 Tm for tracks of 10 m length had to accommodate the contrasting needs for a field level inside the RICHs envelope less than 2 mT and a field as high as possible in the regions between the vertex locator, and the Trigger Tracker tracking station [26]. The design was also driven by the boundary conditions in the experimental hall previously occupied by the DELPHI detector. This implied that the magnet had to be assembled in a temporary position and to be subdivided into two relatively light elements. The DELPHI rail systems and parts of the magnet carriages have been reused as the platform for the LHCb magnet for economic reasons. Plates, 100 mm thick, of laminated low carbon steel, having a maximum weight of 25 tons, were used to form the identical horizontal bottom and top parts and the two mirror-symmetrical vertical parts (uprights) of the magnet yoke.[1] The total weight of the yoke is 1500 tons and of the two coils is 54 tons.

The two identical coils are of conical saddle shape and are placed mirror-symmetrically to each other in the magnet yoke. Each coil consists of fifteen pancakes arranged in five triplets and produced of pure Al-99.7 hollow conductor in an annealed state which has a central cooling channel of 25 mm diameter. The conductor has a specific ohmic resistance below $28\,\Omega\cdot$ m at 20°C. It is produced in single-length of about 320 m by rotary extrusion[2] and tested for leaks with water up to 50 bars and for extrusion imperfections before being wound. The coils were produced in industry[3] with some equipment and technical support from CERN. Cast Aluminum clamps are used to hold together the triplets making up the coils, and to support and centre the

[1] Jebens, Germany.
[2] Holton Machinery, Bournemouth, UK.
[3] SigmaPhi, Vannes, France.

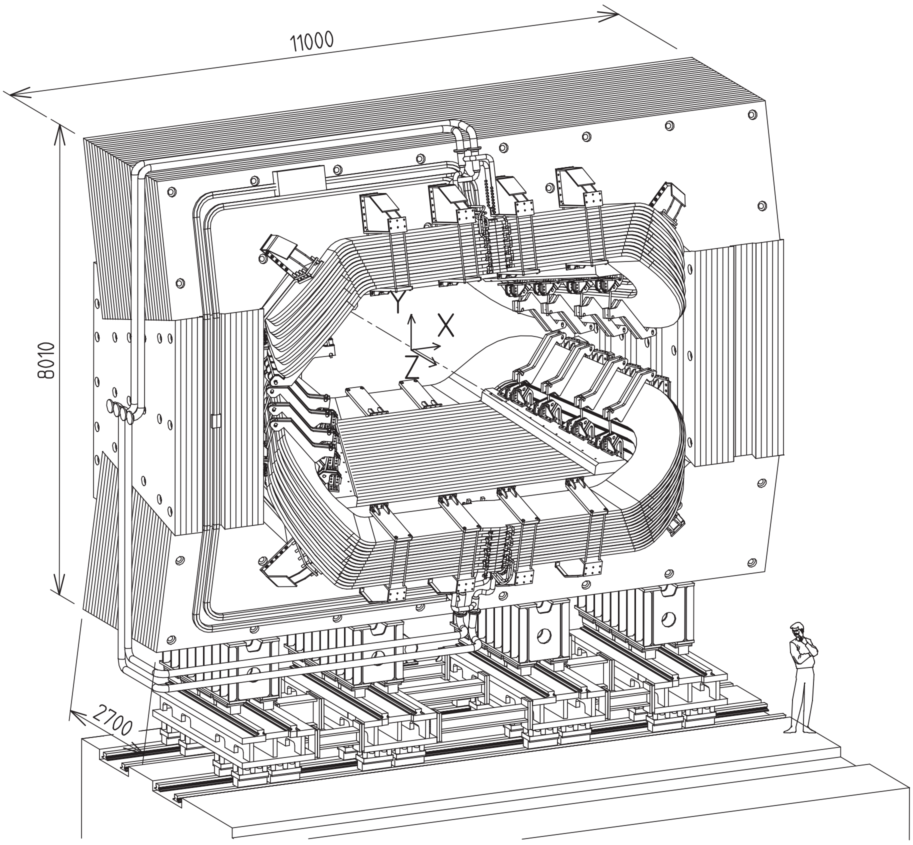

Figure 4.1: Perspective view of the LHCb dipole magnet with its current and water connections (units in mm). The interaction point lies behind the magnet.

coils with respect to the measured mechanical axis of the iron poles with tolerances of several millimeters. As the main stress on the conductor is of thermal origin, the design choice was to leave the pancakes of the coils free to slide upon their supports, with only one coil extremity kept fixed on the symmetry axis, 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 respect to the effect of the electromagnetic and thermal stresses on the conductor, and the measured displacement of the coils during magnet operation matches the predicted value quite well. After rolling the magnet into its nominal position, final precise alignment of the yoke was carried out in order to follow the 3.6 mrad slope of the LHC machine and its beam. The resolution of the alignment measurements was about 0.2 mm while the magnet could be aligned to its nominal position with a precision of ± 2 mm. Details of the measurements of the dipole parameters are given in table 4.1. A perspective view of the magnet is given in figure 4.1.

The magnet is operated via the Magnet Control System that controls the power supply and monitors a number of operational parameters (e.g. temperatures, voltages, water flow, mechanical movements, etc.). A second, fully independent system, the Magnet Safety System (MSS), ensures the safe operation and acts autonomously by enforcing a discharge of the magnet if critical parameters are outside the operating range. The magnet was put into operation and reached its nominal

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Table 4.1: Measured main parameters of the LHCb magnet.

Non-uniformity of $\|B\|$	$\pm 1\%$ in planes xy of 1 m^2 from z=3m to z=8 m
$\int Bdl$ upstream TT region (0–2.5 m)	0.1159 Tm
$\int Bdl$ downstream TT region (2.5 - 7.95 m)	3.615 Tm
Max field at HPD's of RICH1	20×10^{-4} T (14×10^{-4} T with mu-metal)
Max field at HPD's of RICH2	9×10^{-4} T
Electric power dissipation	4.2 MW
Inductance L	1.3 H
Nominal / maximum current in conductor	5.85 kA / 6.6 kA
Total resistance (two coils + bus bars)	R = 130 $m\Omega$ @ 20° C
Total voltage drop (two coils)	730 V
Total number of turns	2 x 225
Total water flow	150 m^3/h
Water Pressure drop	11 bar @ ΔT = 25°C
Overall dimensions H x V x L	11m x 8 m x 5 m
Total weight	1600 tons

current of 5.85 kA in November 2004, thereby being the first magnet of the LHC experiments operational in the underground experimental areas. Several magnetic field measurement campaigns have been carried out during which the magnet has shown stable and reliable performance.

4.2 Field mapping

In order to achieve the required momentum resolution for charged particles, the magnetic field integral $\int Bdl$ must be measured with a relative precision of a few times 10^{-4} and the position of the B-field peak with a precision of a few millimetres. A semi-automatic measuring device was constructed which allowed remotely controlled scanning along the longitudinal axis of the dipole by means of an array of Hall probes. The measuring machine was aligned with a precision of 1 mm with respect to the experiment reference frame. The support carrying the Hall probes could be manually positioned in the horizontal and vertical direction such as to cover the magnetic field volume of interest. The Hall probe array consisted of 60 sensor cards mounted on a G10 support covering a grid of 80 mm x 80 mm. Each sensor card contained three Hall probes mounted orthogonally on a cube together with a temperature sensor and the electronics required for remote readout. These 3D sensor cards[4] have been calibrated to a precision of 10^{-4} using a rotating setup in an homogeneous field together with an NMR for absolute field calibration [27]. The calibration process allowed correcting for non-linearity, temperature dependence and non-orthogonal mounting of the Hall probes.

The goal of the field mapping campaigns was to measure the three components of the magnetic field inside the tracking volume of the detector for both magnet polarities and to compare it to the magnetic field calculations obtained with TOSCA.[5] For the measurement of CP asymmetries it

[4] Developed in collaboration between CERN and NIKHEF for the ATLAS muon system.
[5] Vector Field TM.

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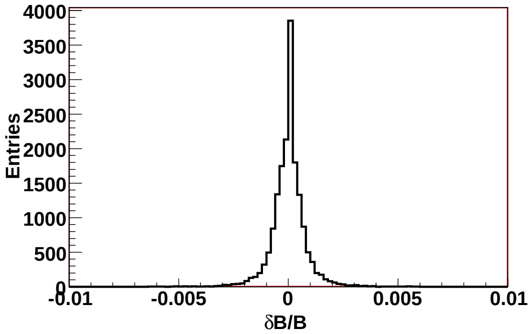

Figure 4.2: Relative difference between the measurements of B using different Hall probes at the same position in the magnet. The resolution is completely dominated by the precision of the calibration of the Hall probes.

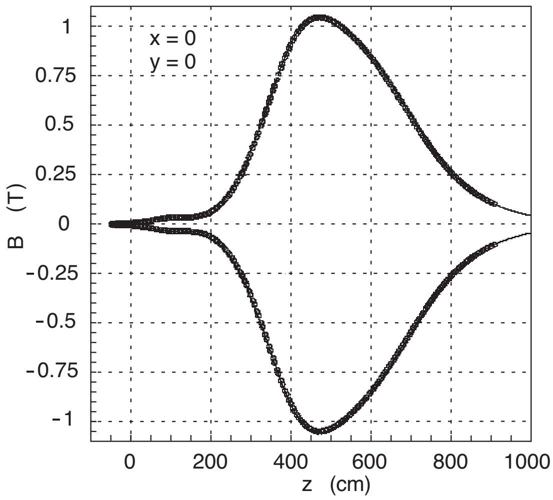

Figure 4.3: Magnetic field along the z axis.

is important to control the systematic effects of the detector, by changing periodically the direction of the magnetic field. To this purpose, the impact of hysteresis effects on the reproducibility of the magnetic field has to be taken into account.

The magnetic field has been measured in the complete tracking volume inside the magnet and in the region of the VELO and the tracking stations, and also inside the magnetic shielding for the RICH1 and RICH2 photon detectors. The precision of the measurement obtained for the field mapping in the tracking volume is about 4×10^{-4}, as shown in figure 4.2. The main component, B_y, is shown in figure 4.3 for both polarities, together with the result of the model calculation. The overall agreement is excellent; however, in the upstream region of the detector (VELO, RICH1) a discrepancy of about 3.5% for the field integral has been found which can be attributed both to the precision of the TOSCA model computation and to the vicinity of the massive iron reinforcement embedded in the concrete of the hall. In all other regions the agreement between measurement and calculation is better than 1%.

In conclusion, the three components of the magnetic field have been measured with a fine grid of 8 x 8 x 10 cm^3 spanning from the interaction point to the RICH2 detector (i.e. over distance of about 9 m) and covering most of the LHCb acceptance region. The precision of the field map obtained is about 4×10^{-4} and the absolute field value is reproducible for both polarities to better than this value, provided the right procedure for the demagnetization of the iron yoke is applied.