Calibration of the CMS Magnetic Field using Cosmic Muon Tracks

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The CMS detector is designed around a large 4 T superconducting solenoid, enclosed in a 12 000-tonne steel return yoke instrumented with muon chambers. Using a large sample of cosmic muon events collected by CMS in 2008, the field in the steel of the barrel yoke has been determined with a precision of 3 to 8% depending on the location.

1 Magnetic field in CMS

The Compact Muon Solenoid (CMS) [1] is a general-purpose detector whose main goal is to explore physics at the TeV scale by exploiting the proton-proton collisions provided by the Large Hadron Collider (LHC) [2] at CERN. During October-November 2008, the CMS Collaboration conducted a data-taking exercise known as the Cosmic Run At Four Tesla (CRAFT) [3]: 270 million cosmic ray triggered events have been recorded with all installed detector systems participating and with the solenoid at a central magnetic flux density of 3.8 T. Using these data it was possible for the first time to probe the magnetic field in the steel of the barrel return yoke using reconstructed muon tracks.

The CMS silicon tracker is located inside the superconducting coil of the CMS magnet. Within that region, the field has a high strength, is relatively homogeneous and has been mapped with an accuracy better than 0.1%. This precision is crucial for physics analyses as it allows accurate measurements of charged particle track parameters near the interaction vertex.

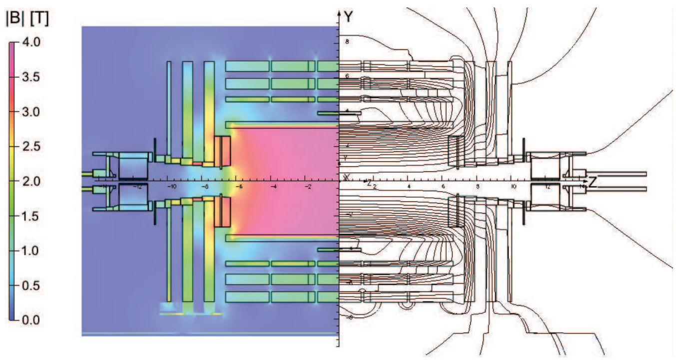

Figure 1: Value of $|B|$ (left) and field lines (right) predicted on a longitudinal section of the CMS detector at a central magnetic flux density of 3.8 T. Each field line represents a magnetic flux increment of 6 Wb.

The CMS barrel yoke is composed of five three-layered dodecagonal barrel wheels. The steel plates of the yoke return the flux of the solenoid and are interleaved with four layers of muon chambers. They serve as absorber and at the same time provide additional bending power for a measurement of the muon momentum independent of the inner tracking system. The resolution in this case is limited by multiple scattering, by the finite resolution of the muon chambers, and by their alignment. To ensure that the systematic uncertainty due to the inaccuracy of the field map is negligible, the benchmark is set at 3% for the overall scale uncertainty and at 5% for the scale in individual plates in the barrel return yoke. These limits are conservative, as they are obtained for the extreme case of a fit with no vertex constraint. With a constrained fit the accuracy of the field in the return yoke can be relaxed by one order of magnitude.

A detailed map of the magnetic field is required for the accurate simulation and reconstruction of physics events. The CMS solenoid and yoke were modeled using the TOSCA finite element program [4]. The predicted magnetic flux density on a longitudinal section of the CMS detector is shown in Fig. 1.

Besides accuracy, computing efficiency of the map interface is a key requirement, as the map is accessed intensively during the on-line reconstruction in the High-Level Trigger. A compact field map of the entire CMS detector has been produced exploiting the 12-fold ϕ-symmetry of the yoke, with special treatment for the sectors affected by the main ϕ-asymmetric features (passages to route connections, supporting feet and carts, the steel plate on the floor).

2 Analysis method and results

The four stations of Drift Tube (DT) chambers which are interleaved with the three steel yoke layers can measure the direction of the track in the transverse plane (ϕ) with a resolution of about 1.8 mrad [5]. The track deflection in the transverse plane between two consecutive stations, i and $i+1$, is related to the average axial component of the magnetic field along the track path in the steel plate (L):

$$(\phi_{i+1} - \phi_i)p_T = -0.3\ q \int_i^{i+1} \vec{u}_\phi \cdot \vec{B} \times d\vec{l} \simeq -0.3\ q \langle B_z \rangle L \tag{1}$$

where q is the muon charge, p_T is the muon transverse momentum in units of GeV/c, B is expressed in Tesla, and L in meters.

Given that the accuracy of the magnetic field map in the region inside the solenoid is very good, the momentum measured by the inner tracker can be taken as reference. The track parameters reconstructed there are extrapolated to the muon spectrometer, where they are compared with the measurements of the muon chamber. The extrapolation of track parameters and of their error matrices is performed taking into account multiple scattering and energy loss.

The correction that has to be applied to the magnetic field map B_z^{map}, in each point within the considered steel yoke plate, in order to obtain the best estimate of B_z^{true} that reproduces the measured track bending as observed in that plate is given by:

$$\frac{[(\phi_{i+1}^{\mathrm{prop}} - \phi_{i+1}^{\mathrm{data}}) - (\phi_i^{\mathrm{prop}} - \phi_i^{\mathrm{data}})] \cdot p_T}{(\phi_{i+1}^{\mathrm{prop}} - \phi_i^{\mathrm{prop}}) \cdot p_T} = \frac{\langle B_z^{\mathrm{map}} \rangle - \langle B_z^{\mathrm{true}} \rangle}{\langle B_z^{\mathrm{map}} \rangle}|_{i+1/i}. \tag{2}$$

where ϕ_i^{prop} and ϕ_i^{data} are the bending angles at the i^{th} DT station for the propagated track and for the track segment reconstructed in the DT chamber, respectively.

Misalignment affects the measured angles of positive and negative muons in the same direction, while a distortion of the field map has an opposite effect on the propagated direction of tracks of opposite charge. The charge-antisymmetric combination of the numerator and denominator of the expression on the left side of Eq. 2 is therefore considered.

The results are listed in Tab. 1.

In order to search for possible biases the correction factors were averaged, grouping steel plates in different ways. For instance, given the propagation direction of the cosmic muons, inaccuracies in the energy loss estimation would be visible as an opposite bias in the scaling factors of upper and lower sectors. No biases are found to exceed the statistical uncertainties (<1%).

	wheels ± 2	wheels ± 1	wheel 0
L1	0.99 ± 0.04	1.004 ± 0.004	1.005 ± 0.005
L2	0.96 ± 0.02	0.958 ± 0.003	0.953 ± 0.003
L3	0.92 ± 0.08	0.924 ± 0.003	0.906 ± 0.003

Table 1: Correction factors of the field map $\langle B_z^{\rm true}\rangle / \langle B_z^{\rm map}\rangle$ for each steel layer, from innermost one to outermost one, averaged between all the sectors in opposite wheels. Reported errors represent the statistical uncertainty only.

2.1 Systematics

Beside the effects of the misalignment and of the energy loss due to the material budget, which have been already mentioned, other systematic effects should be considered.

- The muon segment angle measured in each DT station can be affected by the imperfect knowledge of the internal geometry of the chambers (the assembly procedure can give an uncertainty of 1 mm in the chamber thickness [6]).
- A single correction factor is computed per each steel block for the average B field discrepancy, its local variations within the block are not considered.
- The measured correction factors for all sectors in each layer and wheel, as well as in opposite wheels, are compatible and can be averaged. However, residual differences of up to $\pm 1\%$ in the field integral for a radial path are predicted by the TOSCA model among the sectors where symmetry is assumed to hold.
- The radial component of the field is neglected but its presence affects both the real muon bending and the track extrapolation so a bias on the measured scaling factor is expected only if the ratio $B_r^{\rm true}/B_r^{\rm map}$ differs from the ratio $B_z^{\rm true}/B_z^{\rm map}$

Considering all the statistical and systematic uncertainties, the correction factors of the field map are determined with a precision better than 3% in the three inner wheels, while in the external wheels the precision is about 5% in the innermost yoke steel layer, 3% in the middle one and 8% in the outermost one.

References

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