NORMAL-CONDUCTING SEPARATION AND COMPENSATION DIPOLES FOR THE LHC EXPERIMENTAL INSERTIONS


Abstract
The experimental insertions of the LHC make use of normal-conducting magnets to provide for part of the beam separation and to compensate the effect of two large spectrometer dipoles. Three different types with respect to the length were designed and are based on the same type of lamination. The main type of magnet MBXW has a core length of 3.4 m while the MBXWT and MBXWS magnets are 1.5 m and 0.75 m long versions respectively. The magnet design was done in collaboration between CERN and BINP and the dipole magnets are produced by BINP. So far all three MBXWS magnets, all three MBXWT magnets and fifteen of twenty-nine MBXW magnets have been manufactured and delivered to CERN. The report presents the main design issues and results of the acceptance tests including mechanical, electrical and magnetic field measurements.

INTRODUCTION
The experimental insertions of the LHC make use of normal-conducting magnets to provide for part of the beam separation and to compensate the effect of two large spectrometer dipoles [1]. In the interaction regions IR1 for the ATLAS experiment and IR5 for the CMS experiment, each of the optical elements D1 for beam separation on either side of the experiment consists of 6 MBXW dipoles. Each magnet has a core length of 3.4 m, a large single aperture with a gap height of 63 mm. The magnets are integrated into the optical lattice of the LHC, so a high quality magnetic field must be provided over the entire energy range from 0.45 TeV to 7.5 TeV. This corresponds to a magnetic field ranging from 0.08 T to 1.38 T in the MBXW magnets, with an ultimate field of 1.48 T. The MBXWT and MBXWS magnets are shorter versions of the MBXW magnet and will be used as vertical and horizontal compensation dipoles for the spectrometer dipoles in IR2 for the ALICE and in IR8 for the LHCb experiments respectively. Additionally one MBXW magnet serves as a main compensator for the LHCb experiment.

The report presents the main design issues and results of the acceptance tests including mechanical, electrical and magnetic field measurements.

MAGNET DESIGN AND OPTIMIZATION
The magnet was designed through collaboration between CERN and BINP. One of the main issues in the design was the requirement for the low saturation of the magnetic steel and the size restrictions in order to fit the magnets within the existing LHC tunnels. The numerical design of the insertion magnets was done with the help of the electro-magnetic field computation code MERMAID [2] developed at BINP. This FEM code offers 2D and 3D simulations. The magnet features an H-type shape as this provides the most homogenous field at minimal transversal dimensions (Fig. 1).

Figure 1: Cross-section of the MBXW magnet.

The pole distance measures 63 mm. In order to achieve a good field region of ±41 mm width with a high field quality, the pole width of 240 mm has been chosen. The cross-section of the magnet yoke has been defined with
respect to the pole width and in order to limit saturation effects in the yoke.

The shape of the pole shims in principle should be different for small and large operating fields (Fig. 2). To achieve the required operating range, it has been optimized with an objective function covering various field levels. Requirements for the precision of the pole profile are determined by the tolerances for the field homogeneity.

The modeling of the magnet end profile was carried out in two stages. First, the shape of the chamfer with a slant of 45 degrees has been optimized over the whole operation range by 2D modeling such as to minimize the deviation of the effective length of the magnet from the geometrical length of the yoke. Even though the length of the magnet is much larger than the pole gap, the pole end shape still had to be corrected to limit field errors due to stray fields. In order to guarantee the required field homogeneity, the shape of the end chamfer was corrected by 3D modeling, (Fig. 3-4).

**MBXW MECHANICAL DESIGN**

The main requirements to the MBXW, MBXWT and MBXWS magnets are presented in Table 1. The main principles of the MBXW, MBXWT and MBXWS magnets are similar to the MBW magnets [3]. The dipoles are assembled from two half-cores joined together by tension plates. Such a structure allows opening the magnet without welding after delivery to CERN. The half-cores are made of precision-punched Cockerill-Usinor Magnetil 15D4 steel laminations of 1.5 mm thickness, assembled together with 80 mm thick end plates and 10 mm thick angular plates along the half-cores. The end plates are made from solid steel.

In order to improve the uniformity of magnetic features of the stacks, the laminations are shuffled before the stacking. The shuffling procedure is determined in order to compensate both the thickness variation over the steel sheet and the difference in magnetic features of the packages of steel. In the process of stacking, groups of 27 laminations are alternately rotated relative to the vertical axis. The laminations are uniformly distributed along the stack by compressing them with a tightening force of 100 kN applied every 0.5 m in the process of stacking. After stacking and clamping, the stack is inspected to make sure that the mating surfaces of all laminations are in contact with the reference surfaces of the fixture.

The stacking factor value must be $\geq 98\%$ and its variation must be kept within $\pm 0.2\%$.

Additionally to the control of the laminations, the magnet yokes are checked geometrically at BINP and after delivery to CERN. In order to reach the required

<table>
<thead>
<tr>
<th>Number of magnets</th>
<th>29</th>
<th>3</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mag. field orientation</td>
<td>vertical</td>
<td>horizon.</td>
<td>vertical</td>
</tr>
<tr>
<td>Gap height mm</td>
<td>63</td>
<td>63</td>
<td>63</td>
</tr>
<tr>
<td>Injection field level T</td>
<td>0.083</td>
<td>0.076</td>
<td>0.088</td>
</tr>
<tr>
<td>Nominal field level T</td>
<td>1.29</td>
<td>1.17</td>
<td>1.37</td>
</tr>
<tr>
<td>Ultimate flux density T</td>
<td>1.48</td>
<td>1.28</td>
<td>1.41</td>
</tr>
<tr>
<td>Field quality @ nom.</td>
<td>$\leq 2\cdot 10^{-4}$</td>
<td>$\leq 1\cdot 10^{-3}$</td>
<td>$\leq 1\cdot 10^{-3}$</td>
</tr>
<tr>
<td>Good field region mm</td>
<td>$\pm 41$</td>
<td>$\pm 17$</td>
<td>$\pm 17$</td>
</tr>
<tr>
<td>Nominal current A</td>
<td>$\sim 700$</td>
<td>$\sim 600$</td>
<td>$\sim 730$</td>
</tr>
<tr>
<td>Ultimate current A</td>
<td>830</td>
<td>650</td>
<td>800</td>
</tr>
<tr>
<td>Magnetic length m</td>
<td>3.4</td>
<td>1.53</td>
<td>0.78</td>
</tr>
<tr>
<td>End chamfers mm</td>
<td>43.5</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Cooling circuits</td>
<td>6</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Total mass kg</td>
<td>11500</td>
<td>5800</td>
<td>3000</td>
</tr>
<tr>
<td>Integral field disp.</td>
<td>$\leq 3\cdot 10^{-3}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall width mm</td>
<td>$\leq 870$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coils</td>
<td>2 coils x 48 turns</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conductor h x w mm</td>
<td>18 x 15</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The stacking factor value must be $\geq 98\%$ and its variation must be kept within $\pm 0.2\%$.
field quality, mechanical tolerances are tight. In particular
the planarity and the twist of the MBXW magnets are
verified at the access holes to stay within ±0.2 mm and
1 mrad respectively.

Each magnet has two excitation coils and each coil
consists of three pancakes. Each pancake consists of
2 layers of 8 turns of a hollow copper conductor
(18 mm × 15 mm with a bore of 8 mm in diameter for
water cooling). Each pancake is wound and wrapped
separately with a glass fiber tape for insulation. Then
three pancakes are put together and a ground insulation
layer is applied with a thicker tape. The complete coil is
vacuum impregnated with radiation resistant epoxy resin.
The impregnating compound is composed of 100 parts of
epoxy resin ED-16, 37 parts of maleic anhydride (MA),
20 parts of polyester plasticizer MGF-9 and 0.5 parts of
accelerator triethanolamine (TEA). These materials are
fully mixed, followed by further thorough mixing during
degassing. The resin is vacuum degassed (below 1 mbar
at a temperature of 65-70 °C) until the mixture is free
from air and impurities with low boiling points. For
degassing, the mould with the assembled coils is heated
up to 65-70 °C and evacuated to below 1 mbar during
several hours. The coils are then fully impregnated with
the resin compound. During the impregnation process the
temperature of the resin and the mould are maintained at a
constant temperature.

In the course of manufacturing the prototype coils were
examined by thermal cycling with a heat-up to 90 °C
and subsequent cool-down to 30 °C. The cycle duration is 20
to 30 minutes. A coil is considered to be good if it stands
25 high voltage cycles and subsequent tests of the inter-
turn insulation, and if the insulation shows no cracks,
voids, shells, or de-lamination of the insulation from the
conductor.

MAGNETIC MEASUREMENTS

Magnetic measurements of all the dipoles are done by
BINP using a Hall probe array of 19 Hall probes located
on a common plate. The centers of the Hall probes are
situated in the horizontal plane, with a maximum spacing
of 5.0 mm (the spacing was measured with 5-7 µm
accuracy), transverse to the beam direction, and they
provide a region of measurement of ±45 mm. The Hall
probe array is moved along the magnetic axis by means of
a drive mechanism including a stepping motor, reducer
and high accuracy 1.2 m long screw. The probe
positioning along the axis is precise within 0.1 mm. The
Hall probes are calibrated vs. NMR probes in a special
precise calibration magnet at all the levels of measured
fields. The absolute error of each individual device is
below ±5·10^{-5} T after applying several correction
methods. In the course of measurement the field map was
measured along the magnet in the region of ±2 m relative
to the center, in the current range from 100 A to 830 A.
The measurement step along the beam axis is 2.5 cm in
the central part of the magnet and 1 cm in the stray field
region. Before starting the magnetic measurement, each
magnet undergoes at least 4 current cycles, from 0 to
835 A, at a ramp rate of less than 50 A/s, and a flat-top
stabilization for more than 20 s at the maximum value.
Current regulation always goes from lower to higher
current values. The overshoot at the end of every current
sweep is kept below 0.1 %. The current stability during
the measurement is controlled with a DCCT supplied by
CERN in order to reach a precision of measurement
within the group of MBXW magnets of ±3·10^{-4} [4].

After preliminary measurements, without correction of
the end chamfers, the relevant shimming was performed.
Fig. 5 shows comparative results of magnetic field
integral measurements before and after correction for the
MBXW magnet. Some series magnets have also been
measured magnetically at CERN using a rotating coil
setup. Both methods give comparable results and show a
good agreement of the measurement results with the
design values.

CONCLUSION

The production of the MBXW type magnets at BINP is
well advanced. Magnetic measurement data together with
an inspection report and reception tests establish the
quality assurance record for the acceptance of the
magnets at CERN. The results show that the design
fulfills the specification requirements and confirms the
production methods at BINP. At the moment all twenty-
nine MBXW magnets, three MBXWT magnets and three
MBXWS magnets have been manufactured and delivered
to CERN.

REFERENCES

2004-003-V1, CERN, Geneva, 2004