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NORMAL CONDUCTING SEPARATION DIPOLES FOR THE LHC BEAM CLEANING INSERTIONS

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Abstract

In the Large Hadron Collider (LHC), two straight sections, IR3 and IR7, will be dedicated to beam cleaning [1]. These cleaning insertions will be equipped with normal conducting magnets. MBW magnets are dipole magnets used to increase the separation of the two beams. They have a core length of 3.4 m and a gap height of 52 mm and will operate at a magnetic field ranging from 0.09 T to 1.53 T. Limitations on the dimensions and total weight of the magnet resulted in a special design with a common yoke for the two beams. The orbits of the two beams will be separated horizontally by a distance between 194 mm and 224 mm in the gap of the magnet.

The magnet was designed in collaboration between CERN and BINP. The report presents the main design issues and results of the pre-series acceptance tests including mechanical, electrical and magnetic field measurements.

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***Abstract*-- In the Large Hadron Collider (LHC), two straight sections, IR3 and IR7, will be dedicated to beam cleaning [1]. These cleaning insertions will be equipped with normal conducting magnets. MBW magnets are dipole magnets used to increase the separation of the two beams. They have a core length of 3.4 m and a gap height of 52 mm and will operate at a magnetic field ranging from 0.09 T to 1.53 T. Limitations on the dimensions and total weight of the magnet resulted in a special design with a common yoke for the two beams. The orbits of the two beams will be separated horizontally by a distance between 194 mm and 224 mm in the gap of the magnet.**

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***Index terms*-- LHC, normal conducting magnet, twin aperture design, separation dipole**

I. INTRODUCTION

THE MBW separation magnets will be employed in the beam cleaning insertions of the Large Hadron Collider (LHC) to increase the separation of the orbits of the two counter-rotating beams from 194 mm to 224 mm. While the distance between the two beam orbits is relatively large, they are not separated enough that individual magnets could be used for each beam. Therefore a common magnet structure covers the two orbits, with an unusually large radial aperture. As a consequence, the required high magnetic field quality must be provided not at the magnet center but in a region essentially far from it. The magnets are an integral part of the magnetic structure of the LHC collider ring and a high magnetic field quality must be provided over the whole energy range from 0.45 TeV to 7.5 TeV, which corresponds to a magnetic field from 0.09 T to 1.42 T in the MBW magnets, with an ultimate field level of 1.53 T. A strict requirement is the low saturation of the magnetic steel. The limits in overall transversal dimensions of the magnet due to the LHC installation constraints made this requirement even more stringent.

II. NUMERICAL OPTIMIZATION OF THE POLE PROFILE AND GEOMETRY OF THE MAGNET

All calculations were carried out with the help of the MERMAID code [2] developed at the BINP. This code allows to perform both 2D and 3D electro-magnetic simulations. The pole profile was calculated mainly with the help of the 2D version. Computations of integral fields taking the stray field in the magnet ends into account were performed by the 3D version.

The magnet design is H-type, as it provides the most homogenous field at minimal transversal dimensions. The cross section of the magnet is symmetric relative to the vertical and horizontal planes. Hence, the consideration of only one quadrant is sufficient for a complete model, see figure 1.

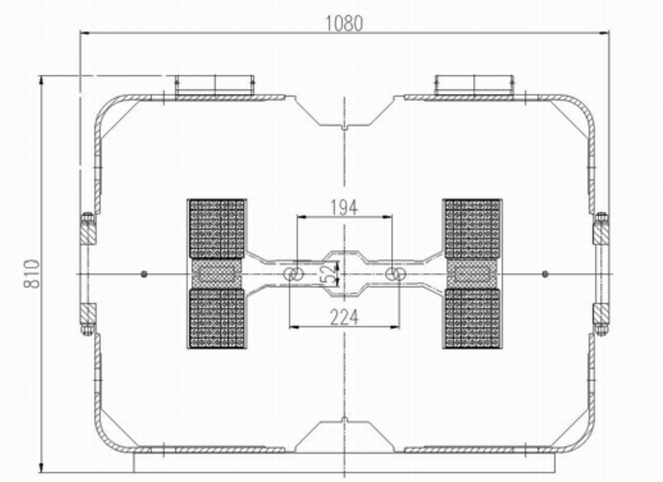

Fig. 1. Cross-section of the MBW magnet.

The gap between the magnet poles is 52 mm high. The mean distance between the two orbits is 209 mm. In order to achieve a "good" field region of ± 25 mm for each of the beams an overall pole width of at least 370 mm is needed (one pole gap added on each side of the edge of the "good" field region). Due to the high requirements on the field quality and the tolerance for the chamfer on the pole end, the pole width is chosen to be 400 mm.

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The section of the magnetic core is chosen to have the most homogeneous induction with respect to the magnetic induction inside the steel. Grooves in the center of the outer shape of the magnet core eliminate unnecessary lamination steel where the induction is low. Grooves in the center of the pole decrease the saturation of the core (see figure 2) and symmetrize, as much as possible, the magnetic field relative to the equilibrium orbits at a distance of ±104.5 mm from the magnet center.

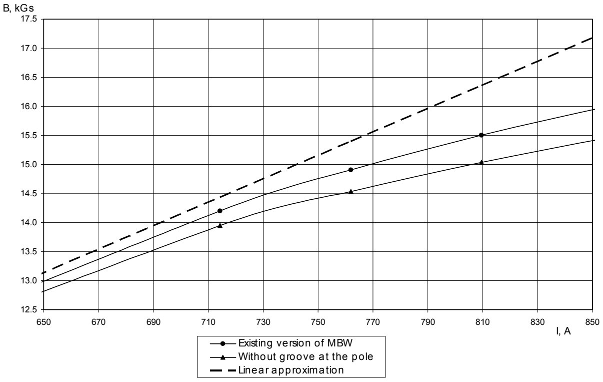

Fig. 2. Decrease of saturation by grooves at the pole.

The shape of the shims, which in principle should be different for low and high working fields, is optimized for the whole operation range.

Requirements in the precision of the pole profile are determined from the tolerances for the field homogeneity. The modeling carried out demonstrates that the flatness of the poles in the apertures is the most critical factor. As second factor comes the height of the right and left shims, see figure 3. Displacement of the edges of the shims and the end chamfers are of smaller influence. The variation of magnetic permeability in different batches of steel influences mainly the fields in the saturation regions.

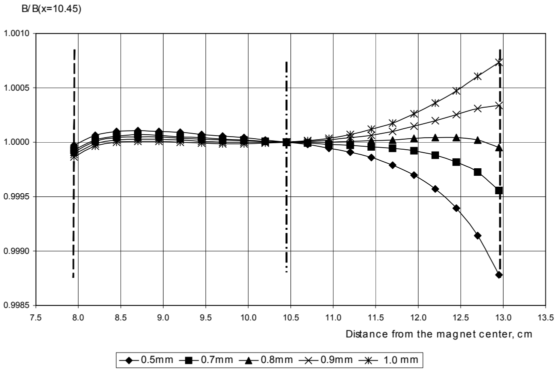

Fig. 3. Dependence of the magnetic field homogeneity from the height of one shim (right). B = 1.42T. The center line gives the median position of the beam. The 2 other lines give the limit of the good field region.

The modeling of the profile of the magnet end was carried out in two stages. At first, the optimal value of the chamfer (the end slant at an angle of 45 degrees) that would provide a minimal difference of the effective length of the magnet from the geometrical length of the magnetic core over the whole operation range of fields was found by 2D modeling.

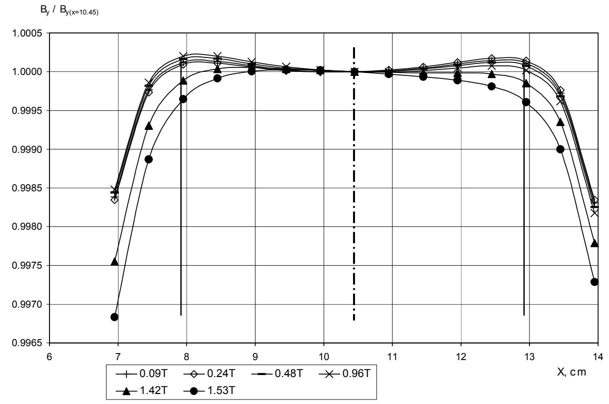

Fig. 4. Relative radial field distribution vs magnetic field.
The center line gives the median position of the beam. The 2 other lines give the limit of the good field region.

However, the stray field on the end of the magnet spoils the homogeneity of the magnetic field integral along the equilibrium orbit, even though the length of the magnet is much larger than the pole gap. So, the shape of the end chamfer was corrected by 3D modeling and the effect was eliminated (figure 4).

III. MBW MAGNET DESIGN

The research performed resulted in the determination of the main requirements for the magnet design. The dipoles are assembled of two half units fixed to each other with tension plates. Such a structure allows to open and close the magnet after delivery to CERN without welding. The half-cores are made of precision-punched Magnetil 15D4 steel laminations of 1.5 mm thickness, assembled together with the help of end-plates of 80 mm thickness and 10 mm thick angular plates in the external outline. In order to improve the uniformity of the magnetic behavior of the stacks, the laminations have been mixed before the stacking. The mixing procedure is determined so that the thickness variation over the steel sheet width is compensated and the effect of differences in magnetic permeability of the steel packs is minimized. In the process of stacking, groups of 27 laminations being stacked 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 after adding 0.5 m length in the process of stacking. Welding of the two angular plates with the end ones and stacked laminations is performed on the stacking fixture.

The stacking factor is significantly influencing the field shape in the gap, see figure 6. Its value must be kept ≥98% with an accuracy of ± 0.2%. The end plates are made from a solid steel block.

The total width of the magnet including the terminals of the current-carrying windings is not more than 1150 mm, and in the region 150 mm above and under the median plane it does not exceed 1020 mm.

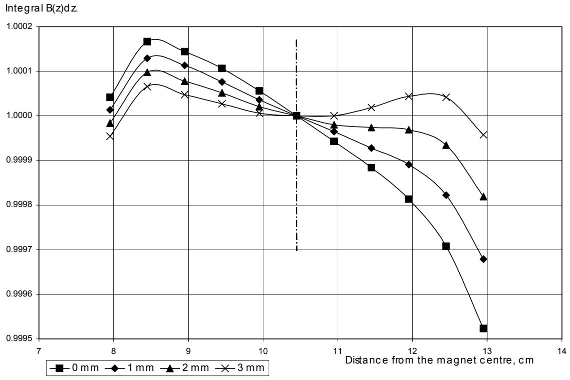

Fig. 5. Dependence of the magnetic field integral homogeneity from the depth of groove at the end chamfer within a interval 5.08…12.5 cm from the centre of the magnet at B = 1.42T.
The line gives the median position of the beam.

Each magnet contains two separate coils. Each coil consists of three pancakes with 2 layers each of 7 turns of a hollow copper conductor with a shape of 18 × 15 mm and a bore of 8 mm in diameter for water cooling. It is insulated with glass-fiber tape and vacuum impregnated by a radiation-resistant epoxy resin. Each of the three pancakes is wound and insulated separately and after assembly they receive an additional insulation and are jointly impregnated.

All joints of the busbar of the coil are brazed with silver solder without flux. Each joint is checked by applying a force of 4×10^5 N/m^2, followed by a helium leakage test. The insulation of the coils is tested after 6 hour immersion in water. In the course of production of the pre-series the coils were tested by thermal cycling: a heat-up to 90°C with a subsequent cool-down to 30°C. The cycle duration was 20 to 30 minutes. A coil is considered to be good if it stands high voltage and checks of the inter-turn insulation after 25 thermal cycles, and the insulation shows no cracks, voids, shells or delamination of the insulation from the conductor. The main requirements of the MBW magnets are presented in Table 1.

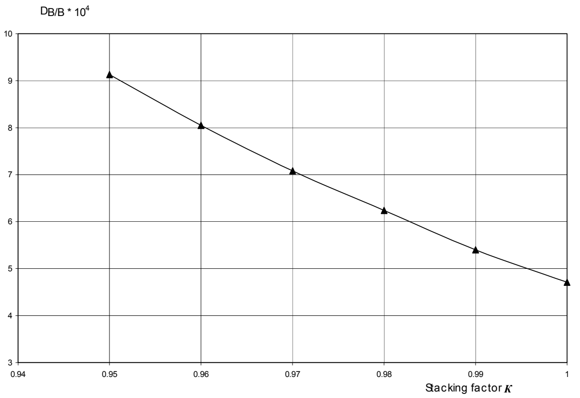

Fig. 6. Dependence of the magnetic field homogeneity within +/-30mm region around the equilibrium orbit from the stacking factor K at B = 1.42T.

IV. RESULTS

Magnetic measurements at BINP were carried out with an array of 19 Hall probes that were fixed on a common plate with equidistant spacing. The centers of the Hall probes are situated in the horizontal plane, with a maximum transverse spacing of 5 mm and provide a region of measurement of ±45 mm. The absolute error of each individual device does not exceed ±5·10-5 T after application of all the correction methods. In the course of measurement of the prototype the field map was made along the length of the magnet in a region of ±2 m relative to the center, in a current range from 100A to 810 A. The measurement step along the beam axis was 2.5 cm in the central region of the magnet and 1 cm in the stray field region. Before the start of the magnetic measurement, each magnet underwent at least 4 slow current cycles from 0 to 810 A at a rate of less than 50 A/s, and a stable flat-top for more than 20 s at the maximum current. Current regulation always proceeds from lower to higher values. At the end of every current ramp the overshoot did not exceed 0.1%.

TABLE I
MAIN PARAMETERS OF THE MBW MAGNETS

Parameter	Quantity
Number of magnets	24
Operating flux density range, T	0.09÷1.42
Ultimate flux density, T	1.53
Field integral quality $\Delta\int B dl / \int B dl$ in the good field region	$\leq\pm5\times10^{-4}$
Good field region, mm, around two orbits, separate by 209 mm	
- At 0.09 T	±25
- At 1.42 T	±12
Nominal current, A, at B=1.42T	720
Ultimate current, A	810
Gap height, mm	52
Magnetic length, m	3.4
Field integral dispersion $\Delta\int B dl / \int B dl$ between the magnets	$\leq\pm3\times10^{-3}$
Overall width in the medium plane, mm	≤1150
Total weight, kg	18 000
Coils	2 coils × 42 turns
Conductor size, mm (height x width)	18 × 15
Water hole diameter, mm	8

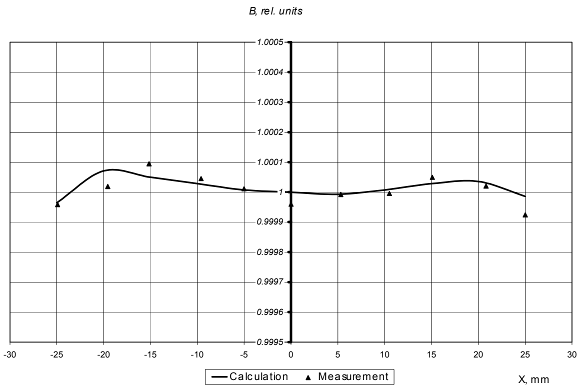

Fig. 7. Magnetic field at the center of the MBW01 magnet. Aperture 2. I=720A.

After preliminary measurements, without correction of the end chamfers of the magnet, the required shimming was performed. Fig. 7 and 8 present for one of the apertures of the MBW magnet the comparative results of the field and magnetic field integral measurement after correction.

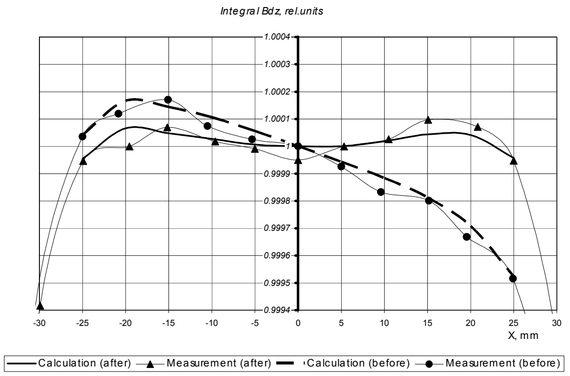

Fig. 8. Magnetic field integral of MBW01 magnet before and after correction at the end chamfers. I = 720A.

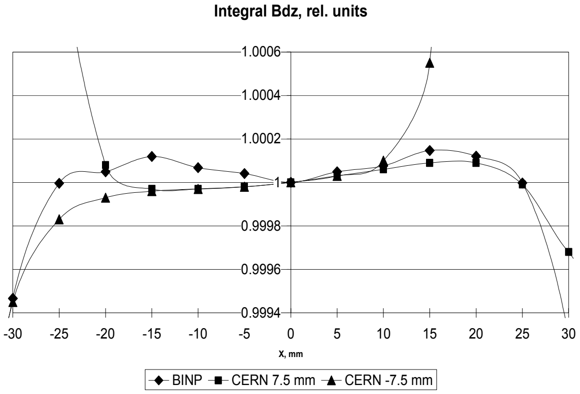

Fig. 9. Comparison between magnetic measurement with the Hall probe array and the mole and I=720 A.
BINP: Measurement with an Hall probe array,
CERN 7.5 mm: measurement with the mole center position at 7.5 mm.
CERN-7.5 mm: measurement with the mole center position at- 7.5 mm.

Magnetic measurements at CERN were performed with application of rotating coils. Both the methods confirm the good agreement of the measurement results with the design values, see Fig. 9. The Taylor series diverges outside the radius of the measurement mole (18.1 mm) and therefore has no significance. The series production of the magnets has been started at BINP.

REFERENCES

[1] The Large Hadron Collider. Conceptual Design. CERN/AC/95-05 (LHC)
[2] MERMAID User Guide, Novosibirsk, 1994