STEEL SEPTUM MAGNETS FOR THE LHC BEAM INJECTION AND EXTRACTION

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Abstract

The Large Hadron Collider (LHC) will be a superconducting accelerator and collider to be installed in the existing underground LEP ring tunnel at CERN. It will provide proton-proton collisions with a centre of mass energy of 14 TeV. The proton beams coming from the SPS will be injected into the LHC at 450 GeV by vertically deflecting kicker magnets and horizontally deflecting steel septum magnets (MSI). The proton beams will be dumped from the LHC with the help of two extraction systems comprising horizontally deflecting kicker magnets and vertically deflecting steel septum magnets (MSD). The MSI and MSD septa are laminated iron-dominated magnets using an all welded construction. The yokes are constructed from two different half cores, called coil core and septum core. The septum cores comprise circular holes for the circulating beams. This avoids the need for careful alignment of the usually wedge-shaped septum blades used in classical Lambertson magnets. The MSI and MSD septum magnets were designed and built in a collaboration between IHEP (Protvino) and CERN (Geneva). This paper presents the magnet design, the experience gathered during the preseries construction, and gives the results of detailed magnetic measurements of the MSIB and MSDC preseries magnets.

1 DESIGN AND PRESERIES CONSTRUCTION

All materials used for the construction of the septum magnets have been carefully chosen in terms of their radiation hardness, magnetic, mechanical, and electrical characteristics.

1.1 Magnetic field calculations

All field calculations [1] were done with the twodimensional finite element code Flux2d. To simplify the geometry, the coils were modelled as rectangular regions, the outer yoke shape was approximated by straight lines, and it is assumed that outside the yoke there is no stray flux. The BH curve was modelled as predicted by the steel maker. The field calculations served to optimise the transverse field homogeneity in the gap by varying the shim dimensions, to estimate the flux leaking into the beam and septum holes, and to develop a concept for shielding the remaining field. The latter is not trivial due to the small distance between the shielding and the inner beam hole surface. Figure 1 shows the flux line pattern in the MSI and MSD. The two types of MSI (MSIA, MSIB) differ by the septum thickness and the field in the gap, obtained by a different number of layers in the coil. Similarly, there are three types of MSD magnets (MSDA, MSDB, MSDC).

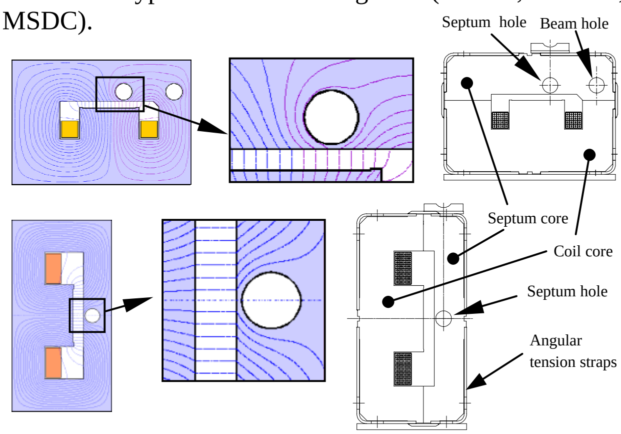

Figure 1: Field model (left) and engineering design (right) of the MSI (top) and MSD (bottom)

1.2 Lamination punching

The laminations are punched out of (1.0±0.02) mm steel sheets of russian type “21848” with a 10 µm thick Fe_3O_4 layer as electrical insulation. The maximum permeability is 4600±80, the coercivity 60±12 A/m. Steel sorting based on the magnetic properties was applied. To avoid an accumulation of systematic thickness differences in the laminations, successive sheets were turned by 180^o about the longitudinal axis, as defined by the sense of the rolling direction, before punching. Prior to stacking the laminations were degreased and weighed, the latter to determine the stacking factor (nominal value: 0.98). The circulating beam holes are punched with precision into the individual laminations, and therefore one avoids a careful alignment of the usually wedge-shaped septum blades used in classical Lambertson magnets.

1.3 Yoke

The yoke is an all-welded construction made from two half-cores (coil-core, septum-core), see Figure 1. The coil-core holds the single pancake coil; the septum-core contains the hole(s) for the circulating beams. The laminations for one half–core are stacked in accurate fixtures to a tolerance of ≤ 0.05 mm from the true horizontal plane and compressed between 30 mm thick non-laminated endplates, using a pressure of 10 daN/cm^2. They are then welded together using angular tension straps that optimise stiffness and reduce sag. The septum-core is longer than the coil core in order to minimise the

the coil core in order to minimise the stray field extending from the field gap to the circulating beam holes. The residual field in the beam and septum holes is shielded by a mumetal layer on the vacuum chamber.

1.4 Coil

The racetrack coils (Figure 2, left) are made from rectangular OFHC copper conductor of outer dimensions 15 mm × 15 mm with a circular cooling hole of 4.5 mm for the MSI and 7.0 mm for the MSD. Each layer corresponds to one cooling circuit with a pressure drop of 5 bar and a temperature increase of 20^{o}C. As interturn and ground insulation, 0.5 mm thick glass fiber tape, treated with amino silane, is used. The coil impregnation is accomplished using radiation hard epoxy resin: Etal-50 liquid modified epoxy resin based on Bisphenol A, Etal-50 acid anhydride hardener, and flexibiliser (diglycidyl ether diethylenglycol). The coil is vacuum impregnated (10^{-3} mm Hg) at a temperature of about 50^{o} C and cured for 2 hours at ~120^{o} C. After cool-down to about 45^{o} C, the mould can be opened and the coil removed.

1.5 Magnet assembly

The coil is inserted into the coil-core, and the coil-core/coil subassembly is supported by a combination of polyurethane and fiberglass spacers. The two halfcores are welded together using steel pads. All pipework for the cooling circuitry is done using stainless steel tubes. Glass fiber / epoxy tubes serve as insulators to separate the current carrrying parts from the ground and the cooling circuit. The coating consists of inorganic zinc silicate primer and two layers of water-based epoxy finish. Table 1 summarises the main parameters, and Figure 2 shows the MSIB01 and MSDC01 preseries magnets. The technical specification is given in [2].

Table 1: MSI and MSD main parameters

Magnetic characteristics	**MSI**		**MSD**		
	A	**B**	**A**	**B**	**C**
Nominal gap field [T]	0.76	1.13	0.80	0.99	1.17
Effective length [mm]	3718	3718	4095	4095	4095
Excitation					
Design current [A]	950	950	880	880	880
Dissipated power [kW]	10.6	15.9	22.7	28.3	34.0
Coil					
Number of layers	4	6	4	5	6
Turns per layer	4	4	8	8	8
Resistance [mΩ]	10.9	16.4	27.1	33.9	40.7
Cooling flow [l/min]	7.9	11.8	16.5	20.7	24.8
Assembled magnet					
Length [mm]	4000	4000	4460	4460	4460
Core width [mm]	734	734	447	447	447
Core height [mm]	529	529	889	889	889
Gap height [mm]	25	25	44	44	44
Septum [mm]	6	15.5	6	12	18
Beam hole [mm]	64	64	64	64	64
Total weight [tons]	9.6	9.7	10.6	10.7	10.8

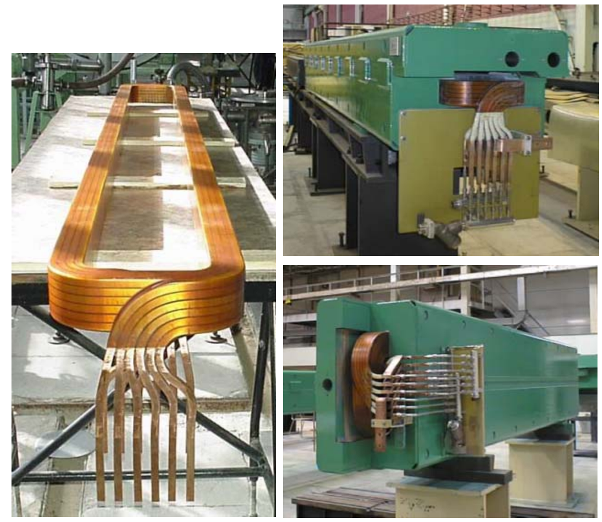

Figure 2: First MSIB coil (left), preseries magnets MSIB01 (top) and MSDC01 (bottom)

2 MAGNETIC MEASUREMENTS

The magnetic measurements aim to verify the field homogeneity in the gap, to measure the magnetisation curve, and to measure the field level in the beam and septum holes with and without shielding. Before shipping the preseries magnets to CERN, extensive and detailed magnetic measurements were carried out by IHEP. The measurements were repeated at CERN [3].

2.1 Magnetisation curve

The magnetisation curve was measured at IHEP using 0.3 mm thick stretched wires spaced 30.31 mm apart. Before each measurement the magnet was demagnetised. The current was ramped to the measurement current, and the integrated induced voltage gives, using proper calibration, the integrated field. The measurement of the magnetisation curve was repeated at CERN using the stretched wire technique. For the MSIB01, the field at nominal current is 8 per mil lower than calculated, again due to the steel permeability. The MSDC01 values correspond to the calculations. The non-linearity of the magnetisation curves is shown in Figure 3, at the operating current corresponding to 1.6 % for the MSIB and to 1.4 % for the MSDC. The IHEP- and CERN-measurements correspond within the quoted experimental errors.

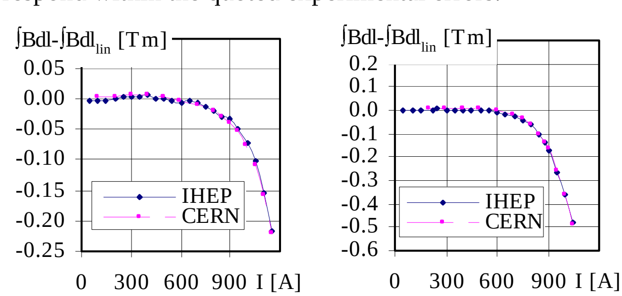

Figure 3: Nonlinearity of magnetisation curves, left: MSIB01, right: MSDC01

2.2 Field homogeneity in the gap

The field homogeneity in the gap was measured by IHEP with an array of 29 Hall probes, mounted on a trolley that is pulled through the magnet and guided by the pole shims. To measure the end field outside the magnet, the pole was extended by non-magnetic material having the same shape as the pole. The magnetic centers of most of the Hall probes correspond to the nominal position within 0.3 mm; the largest deviation measured was 0.5 mm. Their precision is 100 ppm and the long-term drift less than 10 ppm. The transverse positioning of the Hall probes was chosen so that the same array could be used for measuring the MSI as well as the MSD magnets. The measurement of the field homogeneity was repeated at CERN using the stretched wire technique. The gradient observed in the transverse field homogeneity (Figure 5) is expected due to the asymmetry of the magnet. It is higher than estimated due to a lower permeability of the used steel batch, but has been accepted following tracking studies [4]. The MSDC01 homogeneity corresponds to the calculation within the experimental uncertainties.

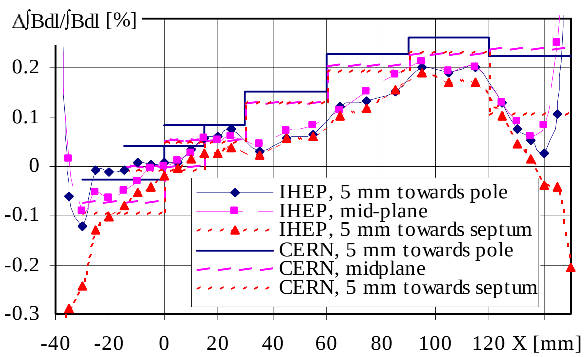

Figure 4: Transverse field homogeneity of MSIB01

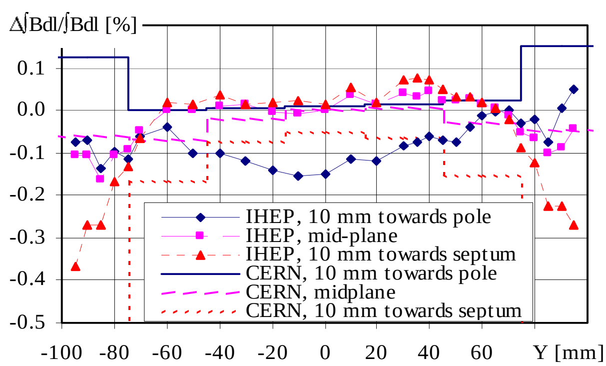

Figure 5: Transverse field homogeneity of MSDC01

2.3 Field in beam and septum holes

The tangential and radial field component in the beam and septum holes was measured at IHEP by two Hall probes, mounted on a rotating shaft. Figure 6 shows the absolute value of the field in the beam and septum holes (without shielding) on a radius of 19 mm as a function of the angle. For the MSIB01 the measured values are about 30 % higher than the calculated values, due to the steel quality. For the MSDC01, the measured values are about 15 % higher. The radial dependence is well described by the measurements, confirming the field calculations. At CERN, only the dipole component in the center of the beam and septum holes was measured and confirms the order of magnitude. The efficiency of the shielding was verified by using several samples close to the final geometry; a reduction below 0.1 Gauss was obtained. The remaining field level has been accepted after comparing the integrated multipolar components to the expected field quality of the LHC main dipoles [5].

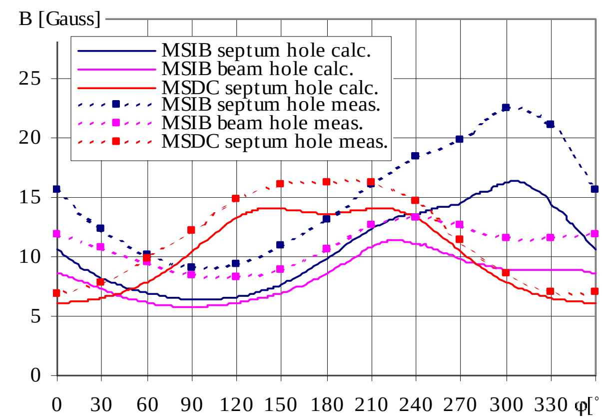

Figure 6: Field in beam and septum holes

3 CONCLUSION

The preseries magnets of the steel septum magnets for the LHC beam injection and extraction have been built by IHEP and measured magnetically at IHEP and CERN. The transverse field homogeneity and the field level in the beam and septum holes fulfil the requirements. The series production has started and the end of the production is foreseen for 2003.

ACKNOWLEDGEMENTS

The authors would like to thank the following individuals for their contributions to this effort: E.Gudkova, P.Korobchuk, A.Kirillov, V.Noskov and N.Yarygin (IHEP). The shielding measurements by R.Chritin (CERN) are gratefully acknowledged.

REFERENCES

[1] M.Gyr: Expected Magnetic Field Quality of the LHC Septum Magnets used for Injection (MSI) and for Extraction to the Beam Dump (MSD), CERN, LHC Project Note 129/rev, November 4, 1999

[2] Technical specification of the steel septum magnets for the LHC injection and beam dumping systems, CERN, SL-Spec. 98-31 (MS), 1998

[3] D.Cornuet, J.Dutour, P.Leclère: Magnetic measurements of the steel septum magnet used for injection: MSIB01, CERN, LHC Project note 280, Dec 2001

[4] M. Meddahi, confirmation by email on 12.4.2001

[5] A. Verdier, confirmation by email on 15.2.2001