OVERVIEW OF THE LHC MAGNETS OTHER THAN THE MAIN DIPOLES

N. Siegel, CERN, Geneva, Switzerland

Abstract

The Large Hadron Collider, due for commissioning in 2005, features a large and complex magnet system that includes about 3000 double aperture magnets and 5000 single aperture ones. Most of these magnets are superconducting, using conductors made of NbTi alloy, with a coil bore of 56 mm and operating in a static bath of superfluid helium at 1.9 K, fully exploiting the conductor limit at these low temperatures. Only a few particular magnets will operate at 4.5 K. For special applications in the long straight sections and for beam injection and extraction, highly specialised room temperature magnets are used. The paper discusses the underlying concepts, which lead to the design and layout of the interaction region magnets, required to obtain the very demanding beam parameters at the four main LHC experiments. The focus will then be on the magnetic elements of matching regions, dispersion suppressors and main arcs, with a discussion of the functionality of the different magnet families. The report will be concluded with a summary giving the present status of the design, procurement and testing of these magnets.

1 LHC PARAMETERS AND LAYOUT

The main performance parameters of the LHC are shown in Table 1. The machine will also operate for heavy ion physics at a luminosity of about 10^{27} $cm^{-2}s^{-1}$.

Table 1: Main parameters for p-p operation

Centre of mass collision energy	14 TeV
Luminosity	10^{34} $cm^{-2}s^{-1}$
Injection energy	0.45 TeV
Bunch spacing	25 ns
Total crossing angle at IP	300 μrad

The basic layout follows closely that of LEP, featuring eight long straight sections, which house experimental insertions or utilities [1]. The two high luminosity insertions are symmetrically located, with ATLAS at interaction region (IR) 1 and CMS at IR 5. The other two experiments, ALICE optimized for ion operation and LHCb for CP violation studies are located in IR 2 and 8 respectively. The beams cross from one ring to the other only at these four points. IR 2 and 8 contain also the injection systems for the 450 GeV proton beams provided by the SPS. IR 3 and 7 are nearly identical and used for “beam cleaning”. Their function is to safely remove and absorb the beam halo to minimize the background in the experimental detectors and any beam losses in the cryogenic part of the machine. These insertions contain therefore only room temperature magnets, which are robust against radiation produced by the primary beam collimators. IR 4 contains the RF acceleration system, which requires that the beam separation of 194 mm in the arcs be increased to 420 mm to provide sufficient transverse space for the cavities. IR 6 contains the beam abort system, which will extract the LHC beams and safely dump them in massive absorbers placed 700 m downstream of the extraction points.

2 EXPERIMENTAL INSERTIONS

2.1 Detector magnets

Large magnet systems are presently being built by the four main LHC experiments to be used for particle identification and momentum measurements [2].

ATLAS and CMS, the two general purpose p-p detectors use specially developed NbTi superconductors. The ATLAS magnet system is huge: 26 m long and 20 m in outer diameter. It comprises a central solenoid (5.3 m long and 2 T design field), a barrel toroid composed of eight coils symmetrically placed around the beam axis and two end-cap toroids placed at each end inside the barrel toroid. CMS features a large solenoid (12.5 m long with a design field of 4 T). The effect of these magnets on the LHC beams is relatively small but need correction. Toroids have no field along the beam axis. Solenoids however will produce coupling of the horizontal and vertical betatron motions, and distort the orbits due to the crossing angle of the beams at the interaction point (IP). Skew quadrupoles and dipole correctors are foreseen to cope with both effects respectively.

ALICE and LHCb use room temperature magnets. ALICE incorporates the solenoid magnet presently being used by the L3 experiment at LEP and will run it at a field of 0.2 T. Both experiments feature a spectrometer arm each provided with a specifically developed dipole magnet of window frame design and which is traversed by the LHC beams. A local orbit compensation scheme is therefore needed in both cases.

2.2 The inner triplets

The strong focussing at the four collision points is obtained by the low-β quadrupoles of the inner triplets placed symmetrically at a distance of 23 m on each side of the IP (Fig. 1) and shared by both beams. Eight inner triplets will be installed in the LHC and be provided in the frame of the US and Japanese contributions to the

LHC project. There are two types of low-β quadrupoles (Table 2) both with a coil bore of 70 mm. Type MQXA (Q1 and Q3) developed at KEK, Japan, is based on a four-layer coil design using 11 mm graded NbTi cable [3]. Type MQXB (Q2a and Q2b) developed at FNAL, USA is based on a two-layer coil design using a 15.4 mm graded NbTi cable [4]. The main challenges are to fulfil the stringent demands on field quality and to reach high operating gradients. In fact, at collision energy it is mainly the low-β quadrupole fields that govern the dynamic aperture and luminosity.

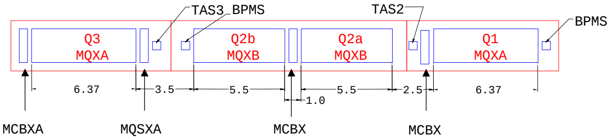

Fig. 1. Schematic layout of inner triplet.

Another serious constraint is imposed by the flux of secondary particles emerging from the p-p collisions. Although an important fraction is absorbed by an upstream collimator the thermal load in each quadrupole remains about 30 W requiring enough thermal margin in the coils to prevent quenching and sufficient cryogenic cooling capacity. Both laboratories have successfully developed short models that reach the required specifications and have launched now the fabrication of full-length prototypes. Sixteen MQXA quadrupoles will be supplied by KEK, produced by Japanese industry, and sixteen MQXB quadrupoles will be made in FNAL. Cold mass integration and cryostating are done by FNAL, including specifically designed corrector magnets supplied by CERN (section 3.4) which compensate the residual field errors and alignment tolerances.

Table 2: Main parameters of low-β quadrupoles

Type	Qty	T op	Lmag	I nom	Gradient
MQXA	16	1.9 K	6.3 m	6450 A	205 T/m
MQXB	16	1.9 K	5.5 m	10630 A	205 T/m

2.3 *Separation dipoles*

The two beams are separated into their respective channels by a pair of bending magnets (D1 and D2) placed immediately after the inner triplet to limit beam-beam effects arising while the beams stay close together.

Dipoles D1 are single aperture magnets. In the high luminosity insertions, due to the high flux of secondary particles coming from the IP, these magnets are warm (six 3.4 m long modules, of type MBXW described in section 5 hereunder). In IR2 and 8 the D1 dipoles are RHIC-style main dipole cold masses (type MBX). Since they are superconducting and have twice the integrated field of the warm D1's, more space is available in these IR's to locate the equipment of the injection systems.

Dipoles D2 are of twin aperture design, using RHIC-type dipole coils pre-stressed with stainless steel collars and placed in a horizontally split yoke (type MBRC). The particularity of this design is that the field in both apertures points in the same direction. To control field asymmetries and saturation effects, sufficient iron is foreseen in the median plane and conveniently placed cutouts are made in the yoke.

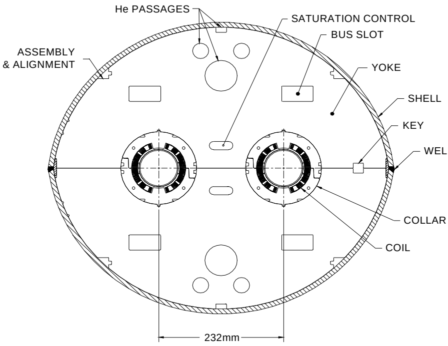

Fig. 2. Cold mass cross-section of D4 (similar to D2).

In the utility insertion 4 that contains the RF equipment the separation dipoles are of similar design. In this case, magnets D3 and D4 increase the beam separation from the standard 194 mm in the arcs to 420 mm in the insertion so that independent cavities can be installed in both beams. For D3, two RHIC-style cold masses called type MBRS are placed side by side in a common cryostat. For D4 (Fig. 2) the design of D2 is adopted with the same cold mass outer dimensions, only aperture separation and yoke cutouts are adapted, giving rise to types MBRA (D4/a) and MBRB (D4/b). These dipoles have a coil bore of 80 mm, are straight and have all a magnetic length of 9.45 m (Table 3). They will be provided with their cryostats by BNL, USA in the frame of the US contribution to the LHC [5]. The cable is now in production and magnet manufacture at BNL will follow.

Table 3: Main parameters of dipoles D1, D2, D3, D4

Type	Qty	T op	Ap. sep	I nom	Field
MBX	4	1.9 K	single	5520 A	3.5 T
MBRC	4	4.5 K	188 mm	5520 A	3.5 T
MBRS	8	4.5 K	single	5520 A	3.5 T
MBRA	2	1.9 K	232 mm	5520 A	3.5 T
MBRB	2	1.9 K	194 mm	5520 A	3.5 T

2.4 *Insertion matching quadrupoles*

The initially foreseen pairs of standard arc quadrupoles and trim quadrupoles of the dispersion suppressor and matching sections have now been replaced by individually powered quadrupoles of lower current. This scheme allows separate control of both rings, increases the flexibility and performance of the collider and reduces the cost of the powering infrastructure. To this end a twin 56 mm bore quadrupole was designed based on an 8.8 mm NbTi cable, two layer coil, with an operating current below 6 kA [6]. These quadrupoles (type MQM) are foreseen in three different lengths to adapt to the required focussing strength and are operated at either 1.9 K or 4.5 K. In the RF insertion, collared coils inserted in single aperture yokes (type MQR) are used in the section where the beams are 420 mm apart. Two 1 m long MQM model magnets have been built in industry and CERN and tested successfully proving the soundness of the design. The award of the contract for industrial procurement of the MQM magnets is foreseen in the third quarter of this year.

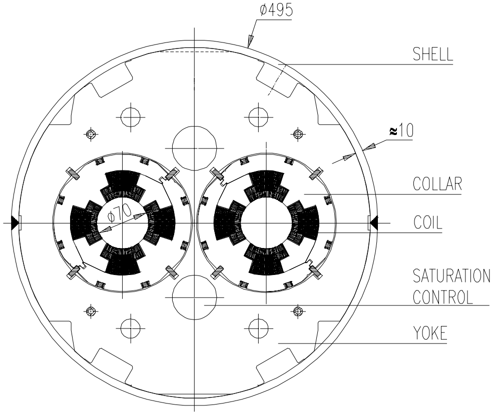

Fig. 4. Cold mass coss-section of MQY quadrupole.

In the experimental insertions close to the inner triplets and close to the injection equipment as well as in the dump insertions close to the extraction equipment, low current twin bore quadrupoles with a wider aperture of 70 mm are needed to match the local geometrical acceptance requirements. These quadrupoles (type MQY) are designed on the basis of an 8.3 mm graded NbTi cable, four layer coil (Fig. 3) and operating at 4.5 K [7]. A twin aperture 1 m long model was built in industry and performed well. The nominal working point of the MQM and MQY quadrupoles is at 80% along the load line and main parameters are shown in Table 4. The procurement of the MQY's is now in the tendering stage.

Table 4: Main parameters of insertion quadrupoles

Type	Qty	T op	Lmag	I nom	Gradient
MQMC	12	1.9 K	2.4 m	5390 A	200 T/m
MQM	38	1.9 K	3.4 m	5390 A	200 T/m
MQM	4	4.5 K	3.4m	4310 A	160 T/m
MQML	32	1.9 K	4.8 m	5390 A	200 T/m
MQR	4	4.5 K	3.4 m	4310 A	160 T/m
MQRL	4	4.5 K	4.8 m	4310 A	160 T/m
MQY	20	4.5 K	3.4 m	3600 A	160 T/m

3 CORRECTOR MAGNETS

3.1 General design and fabrication concepts

About 5000 single aperture and 1000 twin aperture corrector magnets will be made in industry. The development of such magnets started in CERN early in 1990 and a number of collaboration agreements were signed with industry to foster technology transfer and know how in superconducting magnet manufacturing. In order to optimise the cost, a number of design and fabrication principles were developed at CERN and tested:

- Counter-rotating winding for fabrication automation of coils and for eliminating layer jumps (joggles) and spacers.
- Flat multi-wire cable to reduce the number of winding turns when making the coil.
- Iron brought close to the coils, enhancing the field, using so-called scissors laminations made of magnetic material and which transfer the pre-stress.
- Pre-stress applied by shrink rings avoiding the use of a press.

With 194 mm beam separation, there is sufficient lateral space to build all correctors as single modules, with a nominal working point at 60% along the load line. Subsequently, twin aperture units are assembled by keying corresponding modules into laminated support structures. All correctors are cold tested in industry. To reduce He consumption and cost they are tested as single modules instead of as full magnets. Further, the assembly by keying insures mechanical precision and allows flexibility during mounting, since the same type of module is used for a normal or for a skew magnet.

Models and prototype corrector magnets have been made and successfully tested for nearly all designs needed in the LHC. All these units have been cold tested and magnetically measured and the results have been used to optimise the design and streamline the fabrication. One example for instance is that multipole correctors of higher order than the sextupole, i.e. octupole, decapole and 12 pole, are built with half the number of coils, which is more economical. This produces only small asymmetries in the ends, which are acceptable. However, for sextupoles and lower order multipoles, the training behaviour deteriorates and therefore such magnets feature the same number of coils as poles.

The wire is a rectangular or round enamel insulated NbTi monolithic conductor made with a precision of 10 μm. Contracts for industrial procurement have been placed with IGC, USA and Outokumpu, Finland.

3.2 Multipole correctors for main dipoles

Each main dipole will be equipped with a pair of sextupoles "spool" correctors (type MCS) [8], which compensate the sextupole errors of the dipole field up to collision energy, i.e. up to 2.5 units (units of 10^{-4} at a reference radius of 17 mm). The sextupoles are attached to one of the ends of the main dipole, by means of a precise jig, which align them on axis as well as in tilt. Each second dipole will be equipped with a decapole "spool" corrector (type MCD) which also has an octupole insert (type MCO). The complete corrector (MCDO) is placed at the opposite end of the dipole and will compensate the corresponding errors of the dipole field mainly at injection and in the beginning of the ramp. The contracts for both the MCS and MCDO correctors have been placed and the first pre-series MCS correctors have already been supplied by ANTEC, Spain. Fabrication of the MCDO has started at TESLA Engineering, UK. The above two European firms will supply half of the production and the other half will be supplied by CAT (Centre for Advanced Technology, Indore) as part of the Indian contribution to the LHC in the frame of the CERN-India Collaboration Agreement. The main parameters of the "spool" correctors are shown in table 4.

Table 5: Main parameters of "spool" correctors (single bore). Field given at reference radius of 17 mm.

Type	Qty	T op	L mag	I nom	Field
MCS	2464	1.9 K	0.11 m	550 A	0.47 T
MCO	1232	1.9 K	0.066 m	100 A	0.04 T
MCD	1232	1.9 K	0.066 m	550 A	0. 1 T

3.3 *Lattice and orbit correctors*

The following corrector magnets are installed next to each main arc quadrupole [9] in the Short Straight Sections:

- On the end opposite to the connections there is a twin aperture unit (type MSCB) [10] comprising a chromaticity sextupole (MS) and a closed orbit corrector (MCB). The sextupoles are connected in F and D families, but a few are tilted and in separate families to work as skew sextupoles (MSS). The MCB are of low current design individually powered via local 60 A current leads and are alternating horizontally or vertically deflecting.
- On the connection end of the main quadrupole there is either a tuning quadrupole (type MQT), a skew quadrupole (MQS) for coupling correction or a Landau damping octupole (MO), connected in families.

The design concept of the MSCB has evolved from a 1.1 m long nested coil version to a separate sextupole dipole coil version. The coils are now about half as long and the fields are doubled. The advantages are the absence of mechanical and magnetic coupling, improved performance and simpler fabrication techniques. A contract for the industrial procurement of these magnets has now been placed with the firm TESLA Engineering, UK.

In the dispersion suppressor and matching sections longer versions of the tuning quadrupoles are used (type MQTL) and stronger orbit correctors are needed. These correctors (type MCBC) are designed for a current of 110 A, and in some places, e.g. near the MQY quadrupoles, they have an enlarged coil bore of 70 mm (type MCBY). In the RF insertion individual modules of this corrector (type MCBR) are paired with the MQR quadrupoles. Industrial procurement of quadrupole, octupole and stronger dipole corrector magnets (Table 6) is now in the tendering stage.

Table 6: Main parameters of lattice and orbit correctors. For MO field at reference radius of 17 mm.

Type	Qty	T op	L mag	I nom	B/G
MCB	376	1.9 K	0.65 m	55 A	2.9 T
MS	376	1.9 K	0.369 m	550 A	1.28 T
MQT	160	1.9 K	0.32 m	550 A	120 T/m
MQS	32	1.9 K	0.32 m	550 A	120 T/m
MQTL	36	1.9 K	1.3 m	550 A	125 T/m
MQTL	20	4.5 K	1.3 m	400 A	90 T/m
MO	168	1.9 K	0.32 m	550 A	0.29 T
MCBC	78	1.9 K	0.9 m	100 A	3.1 T
MCBR	16	4.5 K	0.9 m	67 A	2 T
MCBY	40	4.5 K	0.9 m	72 A	2.5 T

3.4 *Correctors for inner triplets*

Although great care is taken in the alignment of the low-β quadrupoles, specific correctors are foreseen to correct for the inevitable transverse and roll angle positioning errors. In view of space requirements, these correctors feature nested coils and are designed for high fields. The transverse misalignment is corrected by a nested horizontal-vertical deflecting dipoles (type MCBX) [11] in which a field of 3 T can be oriented in any direction. Roll angle misalignments will be corrected by a skew quadrupole (type MQSX). These magnets (Table 7) are part of the inner triplet cold masses and supported cantilevered from the nearest low-β quadrupole (Fig. 1). To insert special higher-order multipole correcting windings, the MCBX and MQSX have a coil bore of 90 mm. The MCBX near to Q3 incorporates b3 and b6 correction windings and the MQSX incorporates a3, a4 and b4 correction windings. Such windings correct higher harmonics in the low-β quadrupole fields needed to maintain the dynamic aperture of the machine.

Table 7: Main parameters of inner triplet correctors (single bore).

Type	Qty	T op	L mag	I nom	B/G
MCBXH/V	24	1.9 K	0.45 m	550 A	3.3 T
MQSX	8	1.9 K	0.5 m	550 A	30 T/m

3.5 *Dipole correctors for beam crossing angle.*

To avoid parasitic collisions due to the tight bunch spacing of 25 ns, the beams are made to cross at a finite angle at the IP's. An ingenious separation scheme, needing only one dedicated MCBX near Q1 and using otherwise foreseen orbit correctors allows individual control of each beam over the full crossing angle range of ±150 μrad with a comfortable margin of 1.5. In this scheme the standard correctors are used at less than 20% of their strength, leaving ample margin for their normal function [12]. A similar scheme is applied in the orthogonal plane to obtain parallel beam separation needed to keep the beams apart from injection up to the pre-collision state at full energy.

4 PROTECTION AND POWERING

The main dipoles and quadrupoles are protected by specifically designed cold diodes and quench heater assemblies. In view of their specific design, the MQX low-β quadrupoles, the matching quadrupoles MQM and MQY as well as the separation dipoles are equipped with quench heaters. It is presently planned to equip the corrector magnets with parallel resistors which should provide adequate protection for families of series connected magnets combined with energy extraction systems [13].

The total current fed into the LHC cold masses via the current feed boxes is about 3.4 MA. Care and effort were taken in distributing and reducing this amount by adapting layout and magnet designs. Thus bus-bars and current leads are standardised at 0.06, 0.12, 0.6, 6 and 13 kA, the latter for the main dipoles and quadrupoles.

5 ROOM TEMPERATURE MAGNETS

Specialised room temperature (RT) magnets are used in the following areas:

- 360 dipoles (MBI) and 180 quadrupoles (MQI) [14] for the injection transfer lines TI2 and TI8.
- Steel septa for beam injection (MSI) at IR2 and 8 and extraction (MSD) at IR6 for beam dumping.
- Fast kickers [15] for beam injection (MKI) at IR2 and 8 and for extraction (MKD) at IR6. Also fast kickers for beam dilution prior to the dumps and for tune and aperture measurements in the ring.
- In the ring, separation dipole D1 (MBXW) in IR1 and 5, D3 and D4 (MBW) and the quadrupoles (MQW) [16] in the cleaning insertions IR3 and 7, as well as the orbit compensation for ALICE and LHCb each using three RT dipoles (Table 8).

Nearly half of the 6.3 m long MBI dipoles and of the 1.4 m long MQI quadrupoles have been delivered by BINP, Novosibirsk, in the frame of the CERN-Russian Federation collaboration. The steel septa, ten 4 m long units for injection and thirty 4.5 m long units for extraction, will be produced by IHEP, Protvino and tooling and first coils have been made. The highly specialised LHC kickers represent 64 systems covering an impressive 129 m in the machine. Fabrication of the MQW started in Canada (collaboration with TRIUMF, Vancouver) and of the RT separation dipoles in BINP, Novosibirsk.

Table 8: Main parameters of RT magnets in the ring

Type	Qty	L mag	I nom	B/G
MBXW	26	3.4 m	700 A	1.38 T
MBW	20	3.4 m	700 A	1.42 T
MQW	48	0.32 m	710 A	35 T/m

6 CONCLUSION

The design phase of the LHC magnets reported in this paper has been successfully completed and most contracts for industrial procurement have been or will be awarded in the near future. An important part of the magnets are supplied by international collaborations, which are very well advancing. Procurement of these items is therefore well under way and on solid tracks.

ACKNOWLEDGMENTS

The work presented in this paper stems from the activity of numerous teams and groups at CERN as well as from industry and laboratories in many countries which could not all be mentioned explicitly. The author is profoundly grateful for the contributions received by all of them and wishes to acknowledge the hard work and excellent results that have been accomplished.

REFERENCES

[1] L.R. Evans, “LHC Accelerator Physics and Technology Challenges”, PAC’99, New York, Mar 1999.

[2] T.M. Taylor, “The Magnets for the LHC Experiments”, MT16, Ponte Vedra Beach, September1999.

[3] J. Kerby et al. “Recent Results from the LHC Inner Triplet Quadrupole Development Program at Fermilab”, MT16, Ponte Vedra Beach, Sep.1999.

[4] T. Nakamoto et al., “Training Characteristics of 1-m Model Magnets for the LHC low-β Quadrupoles”, MT16, Ponte Vedra Beach, September1999.

[5] P. Wanderer et al. “High Field Magnet Program at Brookhaven National Laboratory”, MT16, Ponte Vedra Beach, September1999.

[6] J. Lucas et al., “Performance of the 1-m Model of the 6 kA Superconducting Quadrupole for the LHC insertions”, MT16, Ponte Vedra Beach, September1999.

[7] R. Ostojic et al., “Design and Fabrication of a 1-m Model of the 70 mm Bore Twin Aperture Superconducting Quadrupole for the LHC Insertions”, MT16, Ponte Vedra Beach, September1999.

[8] M. Allitt et al., “Further Development of the Sextupole and Decapole Spool Corrector Magnets for the LHC ”, MT16, Ponte Vedra Beach, Sep.1999.

[9] T. Tortschanoff et al., “Performance of Series-design Prototype Main Quadrupoles for the LHC”, this conference.

[10] M. Karppinen et al., “Further Development of the Sextupole and Dipole Correctors (MSCB) Magnet for the LHC”, MT16, Ponte Vedra Beach, Sep.1999.

[11] M. Karppinen et al., “Magnetic Performance of First Low-b Dipole Corrector Prototype, MCBX”, EPAC-98, Stockholm, September 1998.

[12] O. Brüning, W. Herr, R. Ostojic, “A beam separation scheme for IP1 and IP5 at the LHC for optics version 6.1”, LHC Project Report 315, November 99

[13] R. Schmidt et al., “Protection of the superconducting Corrector Magnets of the LHC”, this conference.

[14] K.M. Schirm et al., “The Quadrupole Magnets for the LHC Injection Transfer Lines”, MT16, Ponte Vedra Beach, September1999.

[15] L. Ducimetiere et al., “Design of the Injection Kicker Magnet System for CERN’s 14 TeV Proton Collider LHC”, 10th IEEE Pulsed Power Conference, Albuquerque, July 1995.

[16] G. de Rijk et al., “A Twin Aperture Resistive Quadrupole for the LHC”, MT16, Ponte Vedra Beach, September1999.