CHAPTER 8

INSERTION MAGNETS

8.1 OVERVIEW

This chapter deals with the superconducting and normal conducting magnets used in the eight insertion regions of the LHC. Four of these insertions are dedicated to experiments, while the others are used for the major collider systems (one for the RF, two for beam cleaning and one for the beam dump system). The various functions of the insertions are fulfilled by a variety of magnets, most of them based on the technology of NbTi superconductors cooled by superfluid helium at 1.9 K. A number of stand-alone magnets in the matching sections and beam separation sections are cooled to 4.5 K, while in the radiation areas it is planned to install specialised normal conducting magnets. The different magnet types will be described in the frame of the machine sectors to which they belong.

Table 8.1: Types and number of magnets used in the LHC insertion regions

Magnet type	IR1 ATLAS	IR2 ALICE	IR3 Cleaning	IR4 RF	IR5 CMS	IR6 Dump	IR7 Cleaning	IR8 LHCb
Main dipoles and quadrupoles (DS)								
MB	16	16	16	16	16	16	16	16
MQ	2	2	10	2	2	2	10	2
Superconducting insertion quadrupoles and correctors (DS and MS)								
MQMC	2	2	-	2	2	2	-	2
MQM	6	10	-	4	6	2	-	10
MQML	8	6	-	4	8	4	-	6
MQY	2	6	-	4	2	4	-	6
MQTL	2	2	24	2	2	2	24	2
MSCB	2	2	2	2	2	2	2	2
MCBC	12	13	10	8	12	6	10	13
MCBY	6	9		4	6	4		9
Normal conducting quadrupoles (Cleaning insertions)								
MQWA/B(Q4,Q5)	-	-	24	-	-	-	24	-
Superconducting separation dipoles								
MBX (D1)	-	2	-	-	-	-	-	2
MBRC (D2)	2	2	-	-	2	-	-	2
MBRS (D3)	-	-	-	4	-	-	-	-
MBRB (D4)	-	-	-	4	-	-	-	-
Normal conducting separation and correction dipoles								
MBXW (D1)	12	-	-	-	12	-	-	-
MBW (D3)/(D4)	-	-	12	-	-	-	8	-
MCBWH/V	-	-	8	-	-	-	8	-
Inner triplets and associated correctors								
MQXA (Q1, Q3)	4	4	-	-	4	-	-	4
MQXB (Q2)	4	4	-	-	4	-	-	4
MCBX	6	6	-	-	6	-	-	6
MQSX	2	2	-	-	2	-	-	2
Multipole packages	2	2	-	-	2	-	-	2
Normal conducting compensator dipoles in ALICE and LHCb experiments								
MBWMD	-	1	-	-	-	-	-	-
MBXWT	-	2	-	-	-	-	-	-
MBXWH	-	-	-	-	-	-	-	1
MBXWS	-	-	-	-	-	-	-	2

The type and distribution of magnets amongst the eight insertions are summarized in Tab. 8.1. The dispersion suppressors (DS), from Q8 to Q11, include main dipoles, main quadrupoles in the two beam cleaning insertions and special matching quadrupoles and corrector magnets in all other insertions. The matching sections (MS), from Q4 to Q7 (except in the IR6 where Q6 and Q7 are non-existent), include special insertion type quadrupole and corrector magnets. All of these magnets are superconducting, except in the beam cleaning insertions, where normal conducting quadrupoles and corrector magnets are used. The separation dipoles are partly superconducting magnets and partly normal conducting magnets. The magnets of the inner triplets (Q1 to Q3) consist of special high-gradient large-aperture superconducting quadrupoles, together with a number of specific corrector magnets. For the ALICE and LHCb experimental insertions, which both feature large spectrometer dipoles, specific orbit compensator dipoles are used.

8.2 DISPERSION SUPPRESSORS

8.2.1 Main Dipoles in the Dispersion Suppressors

The main dipoles in the dispersion suppressors have the same characteristics and the same cryostats as for the arc, as described in Sec. 7.3 and 7.4 (with a minor difference in the cryogenic circuits in some of the cryodipoles). These dipoles are installed two per half-cell. The half-cell from Q10 to Q11 is longer than the others and the extra length is bridged by a connection cryostat, which is adjacent to quadrupole Q11 in all IRs. The connection cryostats (Sec. 7.9.3) ensure the continuity of the beam pipes, the cryogenic fluids and the electrical bus-bars.

8.2.2 Dispersion Suppressor Quadrupoles

The superconducting quadrupoles in the dispersion suppressors are based on the MQ and MQM-type magnets. The design of these magnets is described in Sec. 7.5 and 8.3.1, respectively. In all insertions, the first quadrupole of the dispersion suppressors next to the arc (Q11) consists of a cold mass containing an MQ quadrupole, an individually powered MQTL trim quadrupole and an MSCB dipole-sextupole corrector. The main parameters of the dispersion suppressor quadrupole cold masses are given in Tab. 8.2. Their cryostats closely follow the design of the SSS cryostat, where the standard section of the vacuum vessel is modified in accordance with the length of the cold mass. The main components of the cryostat are discussed in Sec. 7.5.3.

Table 8.2: Main parameters of the dispersion suppressor quadrupole cold masses

Cold mass position	**Magnets**	**Operating temperature (K)**	**Length (mm)**	**Mass (kg)**	**No. units**
Q11	MQ+MQTL+MSCB	1.9	6620	7416	16
Q10, Q8 (other than IR3/7)	MQML+MCBC	1.9	6620	7416	24
Q10, Q8 (IR3/7)	MQ+MQTL+MCBC	1.9	6620	7416	8
Q9 (other than IR3/7)	MQMC+MQM+MCBC	1.9	8020	9310	12
Q9 (IR3/7)	MQ+2 MQTL+MCBC	1.9	8020	9310	4

Quadrupoles Q8 to Q10 in the Insertions IR 1/2/4/5/6/8

In the experimental, dump and RF insertions, the focusing from Q8 to Q10 is achieved by using twin aperture quadrupoles of MQM-type operating at currents below 6 kA. Each aperture is individually powered which allows the flexibility required for beam optics to be obtained in a cost effective way. The cold masses of the corresponding short straight sections contain one or two MQM-type quadrupoles and one MCBC dipole corrector, as shown in Tab. 8.2.

Quadrupoles Q8 to Q10 in the Insertions IR 3/7

In the cleaning insertions IR3 and IR7, the focusing from Q8 to Q10 (including Q7) is achieved using main arc quadrupoles with the addition of an individually powered MQTL trim quadrupole to provide the required optical tuning. The corresponding cold masses therefore include one MQTL trim quadrupole (except Q9 which has two) and one MCBC for closed orbit correction, in addition to the MQ quadrupoles. The MQ quadrupoles in these two insertions are powered in series with the corresponding main quadrupole circuits in the arc.

8.3 MATCHING SECTIONS

The tuning of the LHC insertions is provided by the individually powered quadrupoles in the dispersion suppressor and matching sections. The matching sections consist of stand-alone quadrupoles arranged in four half cells, but the number and parameters of the magnets are specific for each insertion. Apart from the cleaning insertions, where specialized normal conducting quadrupoles are used in the high-radiation areas, all matching quadrupoles are superconducting magnets. Most of them are cooled to 4.5 K, except Q7 quadrupoles which are the first magnets in the continuous arc cryostat and are cooled to 1.9 K as are the rest of the arc magnets.

8.3.1 Superconducting Matching Quadrupoles

CERN has developed two superconducting quadrupoles for the matching sections: the MQM quadrupoles featuring a 56 mm aperture coil, which are also used in the dispersion suppressors and the MQY quadrupole with an enlarged, 70 mm coil aperture. Both quadrupoles use narrow cables, so that the nominal current is less than 6 kA, substantially simplifying the warm and cold powering circuits. Each aperture is powered separately, but a common return is used so that a three-wire bus-bar system is sufficient for full control of the apertures.

MQM

The MQM quadrupole, Fig. 8.1, consists of two identical, independently powered apertures, which are assembled together in a two-in-one yoke structure. Three versions of the MQM quadrupole are required for the LHC, with magnetic lengths of 2.4 m, 3.4 m and 4.8 m. The main parameters of the quadrupole are listed in Tab. 8.3. In total, 84 MQM magnets are required for the LHC dispersion suppressor and matching sections.

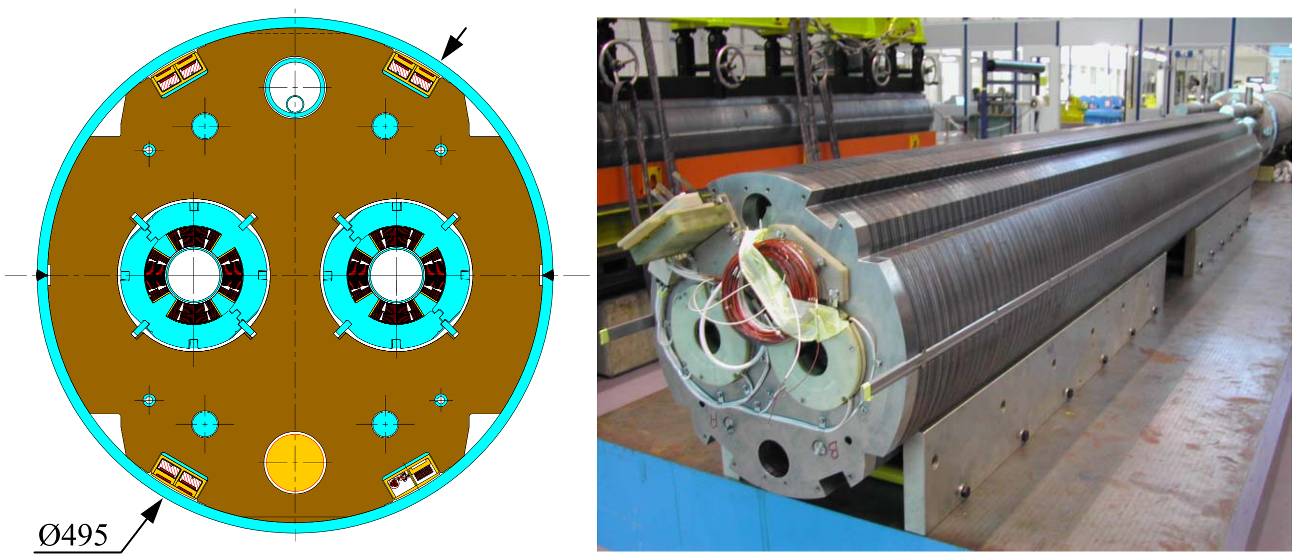


Figure 8.1: Cross-section of MQM quadrupole (left) and a 5 m long MQM magnet on the test stand (right).

The superconducting cable used for MQM quadrupoles is an 8.8 mm wide Rutherford-type NbTi cable formed of 36 strands, each 0.475 mm in diameter. The filament diameter of 6 μm was chosen in order to minimize the effects of the persistent currents at low fields. The cable is insulated with three layers of polyimide film. The first two layers are made of butt wrapped polyimide film (11 mm wide and 25 μm thick), with the second layer offset by half the tape width. The third insulation layer is a 9 mm wide 50 μm thick polyimide film with a 5 μm thick coating of adhesive which cures at 185°C, wrapped with a 2 mm gap.

Table 8.3: Main parameters of the MQM-type quadrupoles

Coil inner diameter	56 mm
Magnetic length	2.4/3.4/4.8 m
Operating temperature	1.9/4.5 K
Nominal gradient	200/160 T/m
Nominal current	5390/4310 A
Cold bore diameter OD/ID	53/50 mm
Peak field in coil	6.3 T
Quench field	7.8 T
Stored energy per aperture	64.3 kJ/m
Inductance per aperture	4.44 mH
Quench protection	Quench heaters, two independent circuits
Cable width	8.8 mm
Mid-thickness	0.84 mm
Keystone angle	0.91 deg.
No of strands	36
Strand diameter	0.475 mm
Cu/SC Ratio	1.75
Filament diameter	6 μm
j_c, (4.2 K and 5 T)	2800 A/mm^2
Mass (2.4/3.4/4.8 m)	3100/4300/6000 kg

The MQM coils are wound out of a single length of insulated cable as a double layer which is cured in a single cycle. The coil design was optimized for the highest transfer function and operational margin and a geometrical b_6 multipole which partially compensates the term due to persistent currents at low currents [1]. The coils are assembled into a collared aperture using 2 mm thick collars, fine-stamped from sheets of high-strength low-permeability steel (yield strength > 620 MPa, relative permeability less than 1.005, both at room temperature). The collars are locked with four full-length tapered keys and provide the necessary compressive stress to withstand the magnetic forces up to the ultimate current.

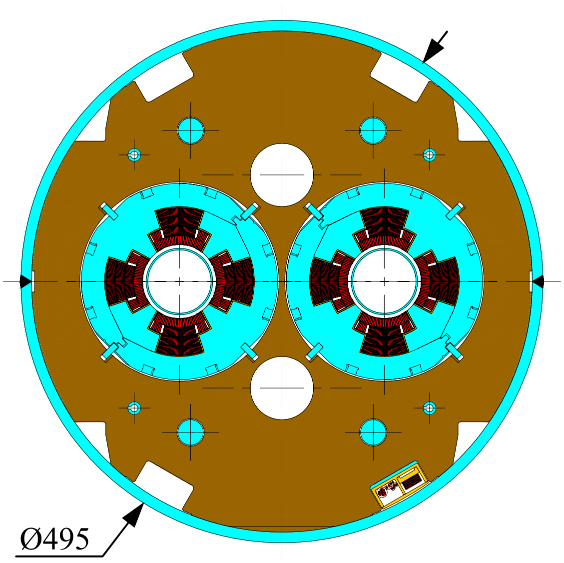
The protection of the magnet during a quench is assured by eight strip quench heaters placed on the outer layer of each coil octant. For redundancy, the heaters are connected in two circuits, such that each circuit covers all four poles and are powered by independent power supplies.

Each collared aperture carries its own connection box. Two completed apertures are assembled in the iron yoke by vertically stacking single-piece laminations. The yoke laminations are similar in design to the LHC arc quadrupole, but are slightly larger (OD 475 mm), so that the outer diameters of the helium vessels are identical. The outer contour of the laminations has alignment and other features necessary for cold mass assembly and longitudinal welding. As the stack is gradually built up, the yokes are compressed and locked with elastic pins, centring at the same time the apertures with four lines of alignment keys. The longitudinal rigidity of the magnet is provided by four tie-rods which link the two end plates.

Measurements of the pre-series MQM magnets have shown that the field quality of the series production can be expected to follow the guidelines set for the arc quadrupoles (see Tab. 7.14). This is in particular the case for non-allowed harmonics of low order where the azimuthal size of the coils plays a dominant role. At the LHC injection energy, the largest fraction of the b_6 multipole is due to the persistent currents, which strongly depend on the powering cycle. Contrary to arc quadrupoles, the MQM quadrupoles have a significant range of currents at injection. Compensation of the persistent current part of the b_6 multipole error with its geometric part is therefore limited in efficiency.

MQY

The MQY wide-aperture quadrupole, Fig. 8.2, consists of two individually powered apertures assembled in a common yoke structure. The coil aperture of the magnet is 70 mm and its magnetic length 3.4 m. The main parameters of the quadrupole are given in Tab. 8.4. In total, 24 MQY magnets are required for the LHC matching sections.



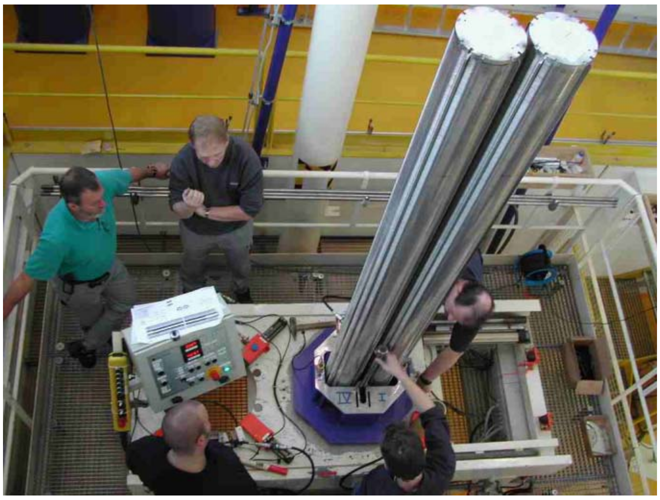


Figure 8.2: Cross-section of MQY quadrupole (left) and assembly of the magnet (right).

Table 8.4: Main parameters of the MQY matching quadrupole

Coil inner diameter	70 mm
Magnetic length	3.4 m
Operating temperature	4.5 K
Nominal gradient	160 T/m
Nominal current	3610 A
Cold bore diameter OD/ID	66.5/62.9 mm
Peak field in coil	6.1 T
Quench field	7.5 T
Stored energy	479 kJ
Inductance	73.8 mH
Quench protection	Quench heaters, two independent circuits
Cable width, cable 1/2	8.3/8.3 mm
Mid-thickness, cable 1/2	1.285/0.845 mm
Keystone angle, cable 1/2	2.16/1.05 deg.
No of strands, cable 1/2	22/34
Strand diameter, cable ½	0.735/0.475 mm
Cu/SC Ratio, cable 1/2	1.25/1.75
Filament diameter, cable 1/2	6/6 μm
j_c, cable 1/2, (4.2 K and 5 T)	2670/2800 A/mm^2
Mass	4400 kg

Two Rutherford-type NbTi superconducting cables are used for winding the MQY coils. They are both 8.3 mm wide, but are made of two types of strands, each strand containing 6 μm filaments. Apart from the diameter (0.735 mm and 0.475 mm), the strands have a different Cu/SC ratio (1.25 and 1.75). The strand and cable parameters were chosen so that the current density in Cable 2 (mid-thickness 0.845 mm) is 1.5 times higher than in Cable 1 (mid-thickness 1.285 mm) for the same current in the cables. The cables are insulated using the same polyimide films and insulation layout as the MQM cable.

The 70 mm aperture MQY coils have four layers, optimized for the highest transfer function and operational field quality [2]. The inner two layers are wound using both types of cable. The first layer and part of the second layer are wound using Cable 1. The transition between the cables is made in an internal joint in the middle of the second layer. Once the winding of the second layer is completed with Cable 2, the two layers are cured together in a single cycle. The outer two layers are wound out of a single length of Cable 2 as a double layer and cured in a single cycle. The connections between the layers, as well as between the poles, are made in the connection box mounted on the end plate of the collared aperture.

As is done for other LHC quadrupoles, the MQY coils are assembled in a collared aperture using 2 mm thick collars fine-stamped from high-strength low-permeability steel. However, due to the large aperture of the coil and the spacing between apertures of 194 mm, the width of the collars is only 22 mm and they need to be locked with eight full-length tapered keys to minimize deformation. In this configuration, the collars provide the necessary compressive stress to withstand the magnetic forces up to an ultimate current of 3800 A at 4.5 K.

The protection of the MQY quadrupole during a quench is assured by sixteen strip quench heaters of two different widths. Eight wide quench heaters are mounted between the second and third layers and the narrow heaters on the outer surface of the fourth layer. This number of heaters is required to limit the voltage during quench in case of failure of some of the heaters. Both the inner and outer heaters are connected in two circuits, each circuit covering all four poles and powered by independent power supplies.

Two completed apertures are assembled in the iron yoke by vertically stacking single-piece laminations (Fig. 8.2). The outer contour of the yoke laminations is identical to the MQM laminations. The position of the heat exchanger hole, however, is displaced towards the centre. Due to the close proximity of the apertures in the two-in-one configuration, the coupling at high currents is considerable and the field quality rapidly degrades above 4000 A. For this reason, the MQY is limited to 3800 A, which in turn means that it can operate at 4.5 K. The internal heat exchanger is therefore not required and its position in the yoke lamination was used to optimize the saturation effects.

The MQY quadrupole was designed with highest field quality in mind. As in the MQM quadrupole, the b_6 multipole has a non-zero geometrical part used to compensate the persistent current effects at injection. However, due to its operation at 4.5 K and larger coil aperture, these effects are smaller than in MQM so that compensation with geometrical b_6 is more effective. Measurements of the pre-series MQY magnets have shown that the field quality of the series production can be expected to follow the specification error tables for the low-β triplet quadrupoles (Sec. 8.5).

Matching Section Cold Masses

The main parameters of the matching section cold masses, which range in length from 5.35 m to 11.45 m, are given in Tab. 8.5. All cold masses (except Q7 in IR3 and 7) are assembled using two welded half-shells as MQM-type helium vessels. Apart from the differences in length, the construction features of the cold masses depend on the operating temperature (1.9 K for Q7 and 4.5 K for all other assemblies), on the powering scheme (e.g. powering through the superconducting link in IR1 and 5) and on the interface details to surrounding elements (e.g. Q4-D2 interconnect).

Table 8.5: Main parameters of the matching section cold masses

Cold mass position	Magnets	Operating temperature (K)	Length (mm)	Mass (kg)	No. units
Q7 (IR4)	MQM+MCBC	1.9	5345	5820	2
Q5, Q6 (IR4) Q4, Q5 (IR6)	MQY+MCBC	4.5	5345	5820	8
Q7 (IR3, 7)	MQ+MQTL+MCBC	1.9	6620	7416	4
Q5, Q6 (IR1, 5)	MQML+MCBC	4.5	6620	8210	8
Q4 (IR1, 5)	MQY+3MCBY	4.5	8020	9310	4
Q7 (IR1, 2, 5, 8)	MQM+MQM+MCBC	1.9	8995	11090	8
Q6 (IR2, 8)	MQM+MQML+MCBC	4.5	10400	12300	4
Q6 (IR3, 7)	6 MQTL+MCBC	4.5	10400	12300	4
Q4, Q5 (IR2, 8)	2 MQY+3 MCBY	4.5	11355	14070	8

MQM-type Helium Vessel

The cold masses containing MQM and MQY quadrupoles are assembled in the Magnet Assembly Facility at CERN in a helium vessel which by its principle is similar to that of the main dipoles. The central elements of the assembly are two 10 mm thick half-shells made of AISI 304L steel which serve for alignment of the various magnetic elements, provide the rigidity and serve as a helium pressure vessel. Contrary to the main dipoles, once welded the half-shells do not participate in compressing the coils or containing the magnetic forces. The vessel is closed with two end covers, which also support the elements required for interconnecting the string of LHC cryo-magnets. In particular, the main 13 kA electrical bus work and 1.9 K helium lines are guided by the end covers and the beam position monitors (BPM) and beam vacuum interconnects are precisely positioned with end covers as reference.

The alignment of the magnets is performed in two steps. In the first step, precision alignment cradles are used to individually align the MQM and MQY magnets, which are not aligned during yoke assembly. The yoke laminations have alignment flats designed as contact surfaces and also as references for control. After compressing the cradles, the alignment of individual magnets is completed by tack welding the alignment keys to the laminations. Subsequently, the individually aligned magnets are placed in the half-shell and aligned relative to each other using the alignment cradles which span the full length of the assembly. The operation is completed with tack welding of the alignment keys to the chamfer of the half-shell.

Several electrical circuits and their instrumentation are installed during assembly. In the first instance, the 13 kA main LHC dipole and quadrupole bus work, although not used for powering the insertion quadrupoles, must be installed in Q7-Q10 cold masses to provide continuity of the arc circuits. Although the design of the bus-bars follows closely that of the main magnets, there are a number of differences, particularly in the position of the expansion loops, Fig. 8.3. Furthermore, as the main quadrupole bus-bars are pulled through after the magnets are aligned in the half-shell, their lead ends have to be bent to their final position in situ.

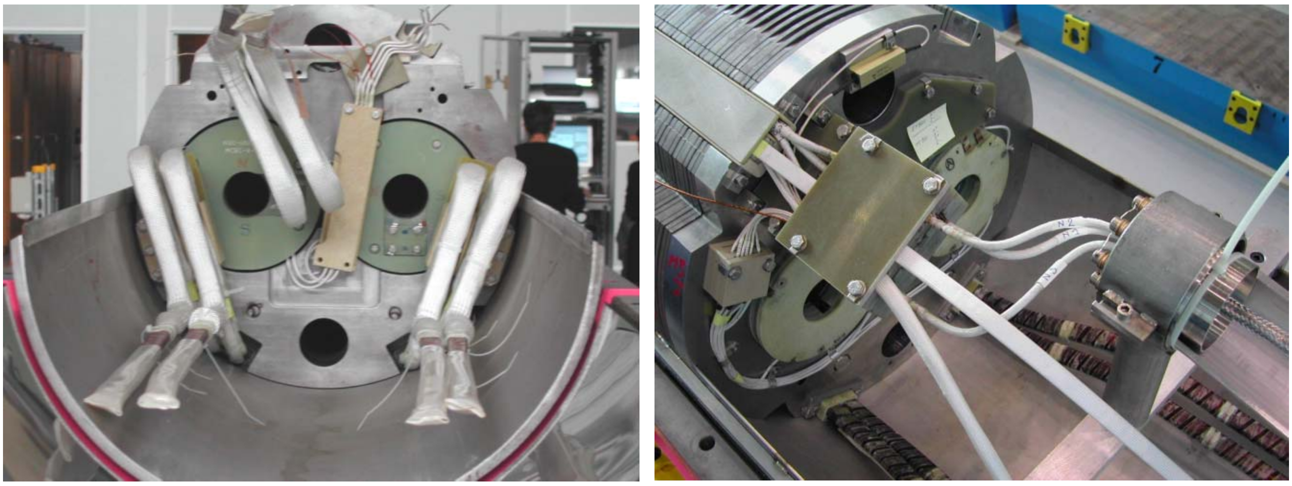


Figure 8.3: (Left) Non-connection side of the Q9 quadrupole showing the MCBC corrector aligned in the half-shell and the expansion loops of the three 13 kA bus-bars. (Right) Lead end of the Q9 quadrupole after completion of the 6 kA splices. The helium tight feed-through for the three 6 kA round wires to line-N is shown on the right. The 13 kA main quadrupole bus bars, bent in situ to their final positions, are in the bottom of the half-shell.

The insertion quadrupoles are powered with three 6 kA round cables routed through line-N (Sec. 7.3.7). In those quadrupoles which comprise two magnets, the apertures are powered in series and the bus-bars connecting the magnets are also 6 kA round cables. Several splices between the 6 kA round cables and the magnet Rutherford-type cable are therefore required. The connections on the lead end of the quadrupole, Fig. 8.3, are particularly challenging due to the large number of splices and tight space. The same technique is used for interconnecting the 6 kA bus-bars with the leads of the second magnet.

The cold bore tubes and heat exchanger tubes are mounted after magnet alignment and before longitudinal welding of the cold mass. The cold bore tubes for the MQM quadrupoles have the same dimensions as those for the arc quadrupole (Sec. 7.5). For the MQY quadrupoles, cold bore tubes have an outer diameter of 66.5 mm and wall thickness of 1.8 mm. Both types of cold bore tubes are insulated with 60 mm wide polyimide tape AST 252 with a 48% overlap. The heat exchanger tubes (mounted in the cold masses cooled at 1.9 K) are copper tubes equipped with stainless steel sleeves at both ends. Apart from the length, they are identical to those mounted in the arc quadrupoles.

The longitudinal welding of the half-shells is performed in the 17 m welding press, previously used for the main dipole prototypes. The welding procedure is a MIG process with three passes. The weld is performed in a cavity formed by the shell chamfers and the alignment key, having the function of a backing strip, Fig. 8.4. Before welding, the press is activated to bring the root faces of the two half-shells in contact over the full length (Fig. 8.4, left). Since the inner circumference of the half-shells is slightly larger than the yoke by 3 mm (corresponding to the weld shrinkage) there is no force on the magnet structure. After welding, the shells and the laminations are brought in contact around the circumference by a small azimuthal stress.

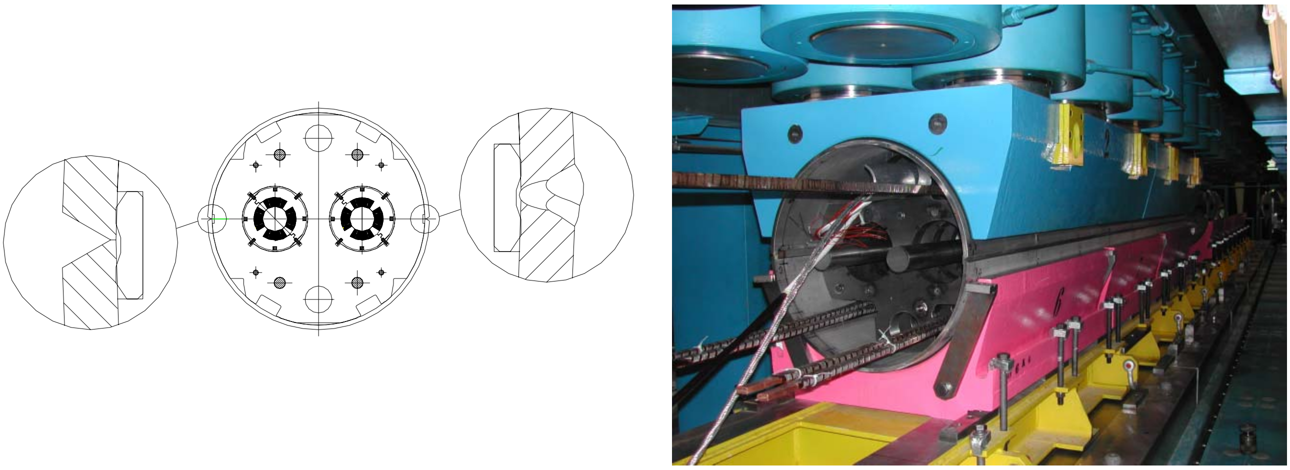


Figure 8.4: (Left) Geometry of the longitudinal weld: detail at left is before welding, detail at right shows the position of the three welding seams. (Right) Q9 quadrupole in place for longitudinal welding.

The end covers of the helium vessel are similar to those of the LHC main dipole. However, many of their features are quadrupole-specific (e.g. cryogenic pipes, BPM supports). As the tolerances are very tight, special tools and procedures are necessary for their assembly. One of the most critical assembly stages is the welding of the end covers. Prior to this operation, the shells are cut to precise length and machined for mounting of the adapting rings, which compensate for the difference in outer diameters of the shell and the end covers. Due to the importance of the final positions of the cryogenic pipes, the positioning of the end covers is controlled with a laser tracker. Before the final orbital weld, the end covers are tack welded and their position adjusted, as shown in Fig. 8.5. The last step in completing the quadrupole extremities is the mounting of the BPM supports, also precisely controlled with a laser tracker.

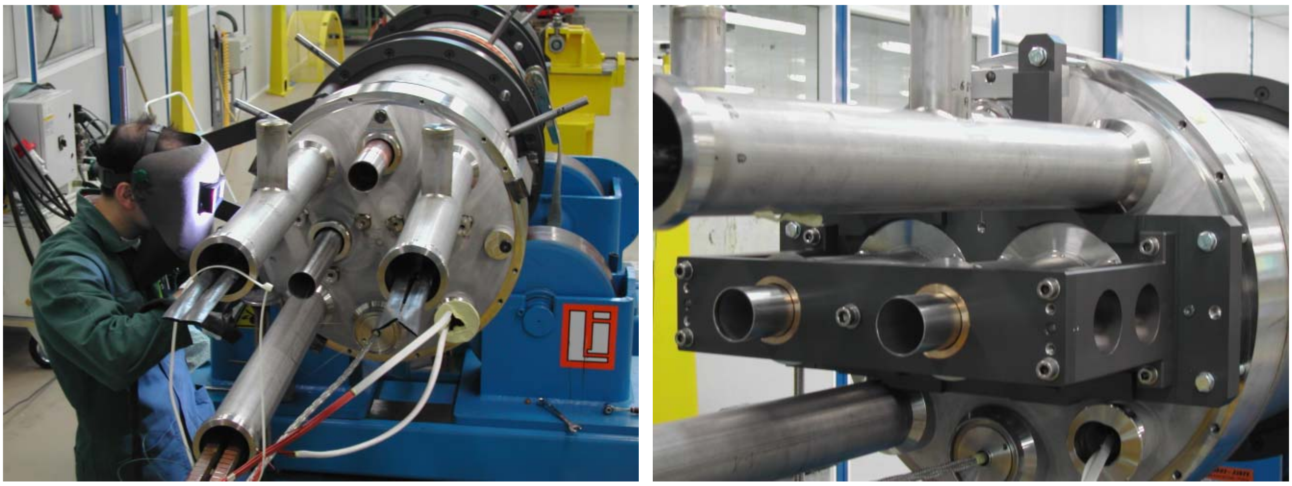


Figure 8.5: (Left) Positioning of the end covers before final orbital welding. (Right) Positioning of the BPM supports on the connection end of the Q9 quadrupole.

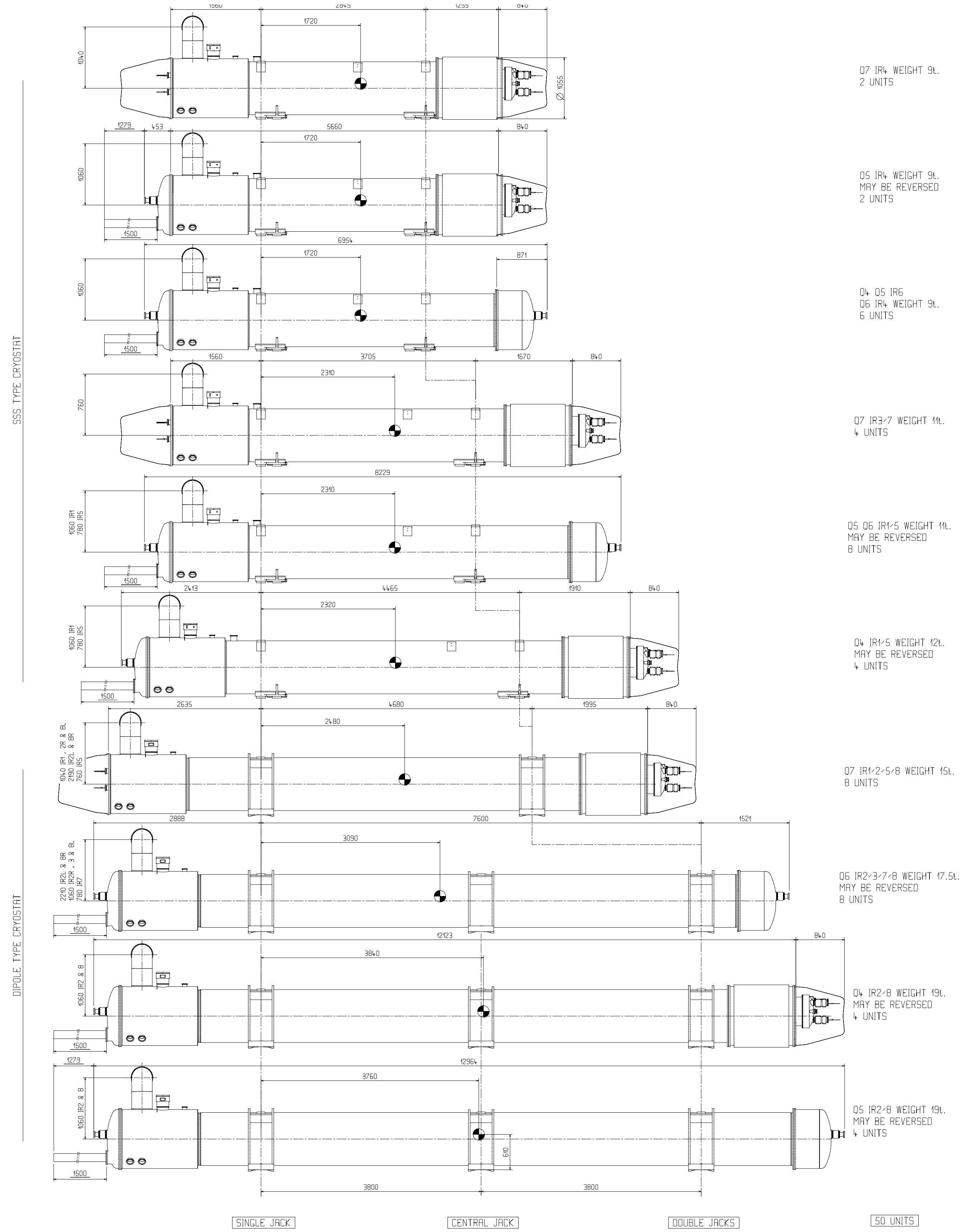


Figure 8.6: Longitudinal view of the matching section cryostated quadrupole assemblies.

Matching Section Cryostats

The cryostats of the matching section quadrupoles were designed by extending the solutions developed for the arc cryostats as far as practical. In particular, the cross-section features of the cryostat (vacuum vessel diameter and thickness), the thermal shields, the MLI blankets and composite support posts were all kept the same. For all cold masses where the length and mass allowed, a two-point support design developed for the arc SSS was preferred. For the longest and heaviest cold masses, however, a three-point support of the dipole vacuum vessels had to be adopted in order to limit the cold mass deflection. As a result, there are six lengths of cryostats, Fig. 8.6, including the additional variants for the stand-alone units.

In addition to the variety of cold masses, the SSS for the matching sections have to accommodate the very specific features imposed by the topology of the machine. For instance, the Q6 quadrupole cryostats in the injection areas (IR2 and IR8), as well as in IR6, must be modified to allow sufficient clearance for the injection and ejection beam lines, respectively. On the other hand, due to the LHC tunnel slope, stand-alone units have to be positioned in such a way as to allow clear venting paths for the boil-off from the 4.5 K saturated helium baths. Also due to the tunnel configuration, the Q7 quadrupoles on the left side of IR4, 5 and 7 are cooled by heat conduction to the 1.9 K heat exchanger of the upstream dipole. In spite of considerable effort to standardize the design, the specific features of the cold masses and cryostats result in 20 different types of cold mass assemblies and 26 different types of cryo-assemblies for a total of 50 matching section quadrupoles [3].

Testing of the Matching Section Quadrupoles

The large number of variants of the dispersion suppressor and matching section quadrupoles raise the issue of their final cold testing. Although in principle the infrastructure and the test capacity exist in the SM18 hall (see Sec. 7.7), the tests of these special magnets is made more difficult because they require additional equipment and in particular the length of time necessary for setting-up and execution of the tests. It is therefore not excluded that the test programme for a subset of these magnets is considerably reduced, or even that some magnets are installed without testing. In order to partially compensate for this possibility, the individual MQM and MQY magnets are tested as far as possible in the vertical cryostat in Block 4 before their assembly and closure in the helium vessel. These tests are focused on the electrical integrity and quench training. The magnetic field quality of the magnets, as well as the alignment of the cold masses are checked by warm measurements, which are used for inferring the performance of the magnets at operating temperatures, in case these are not directly measured.

8.3.2 Normal Conducting Matching Quadrupoles

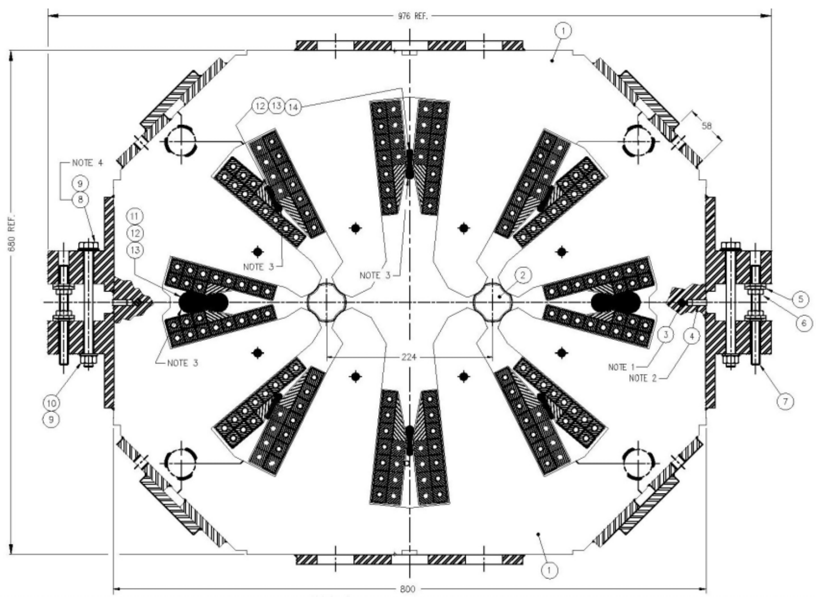


Figure 8.7: Cross-section of the MQW twin aperture normal conducting matching quadrupole.

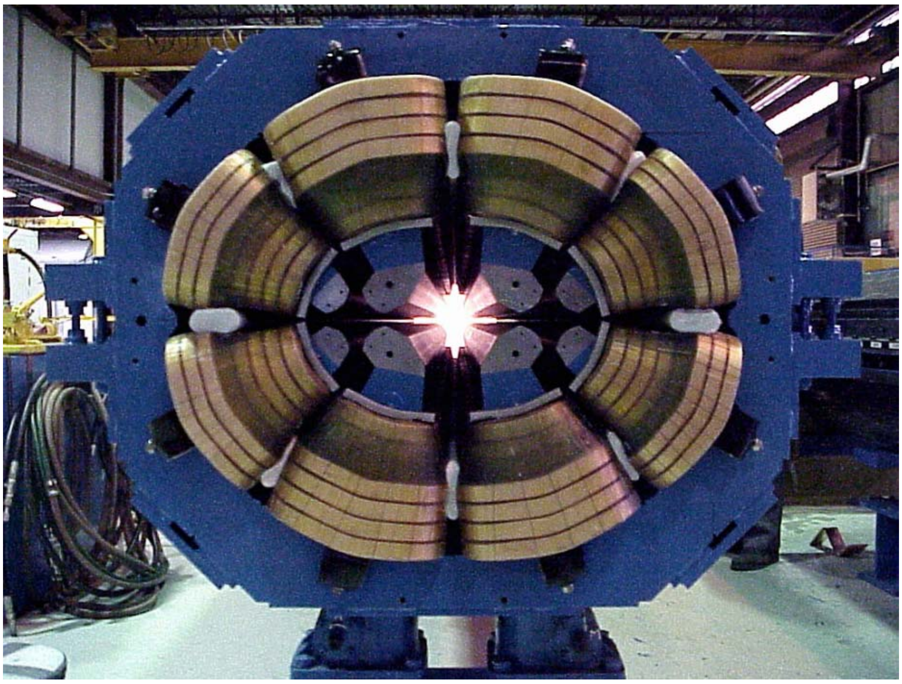


Figure 8.8: End view of the MQW twin aperture normal conducting matching quadrupole.

Table 8.6: Main parameters of the MQW normal conducting quadrupole magnet.

Magnet type	**MQWA**	**MQWB**
Magnetic length	3.1 m	
Beam separation	224 mm	
Aperture diameter	46 mm	
Operating temperature	< 65º C	
Nominal gradient	35 T/m	30 T/m
Nominal current	710 A	600 A
Inductance	28 mH	
Resistance	37 mΩ	
Conductor X-section	20.5 x 18.0 mm² inner poles 17.0 x 17.0 mm² outer poles	
Cooling hole diameter	7 mm inner poles, 8 mm outer poles	
Number of turns per magnet	8 x 11	
Minimum water flow	28 l/min	
Dissipated power at I_{nom}	19 kW	14 kW
Mass	11700 kg	

In the cleaning insertions IR3 and IR7, each of the matching quadrupoles Q4 and Q5 consists of a group of 6 normal conducting MQW magnets. This choice is dictated by the high radiation levels due to scattered particles from the collimation system and therefore the use of superconducting magnets is not possible. The cross-section of the quadrupole is shown in Fig. 8.7 and features two apertures in a common yoke (2-in-1), which is atypical for normal conducting quadrupole magnets but is needed because of transverse space constraints in the tunnel. The two apertures may be powered in series in a standard focusing/defocusing configuration (MQWA), or alternatively in a focusing/focusing configuration (MQWB) in order to correct asymmetries of the magnet. In a functional group of 6 magnets, 5 are configured as MQWA corrected by one configured as MQWB. As in most normal conducting magnets, the field quality is iron-dominated and therefore defined by the shape of the magnetic poles. In order to achieve the necessary field quality, the separation between poles is adjusted and verified to within a tenth of a millimetre by tightening rods along the length of the magnet. The total number of quadrupole magnets in each of the two insertions is 24. Altogether 52 magnets of this type including 4 spares have been built by Canadian industry in collaboration with TRIUMF and CERN. A view of the end of such a quadrupole is shown in Fig. 8.8. The design is given in [4, 5, 6] and the design parameters in Tab. 8.6. The field quality of the production magnets, based on measurements made on 22 quadrupoles is given in Tab. 8.7.

Table 8.7: Field quality of the production MQW quadrupoles at 35 T/m (units of 10^{-4} at 17 mm).

	Measured Average	Measured rms.
b1	-16.11	58.62
b2	10 000	0
b3	39.13	5.60
b4	4.12	2.09
b5	5.74	0.64
b6	-1.09	0.26
b7	-1.81	0.17
b8	0.05	0.07
b9	0	0
b10	0.97	0.03
a1	5.05	46.36
a2	0	0
a3	0.33	3.99
a4	-0.08	1.31
a5	-0.04	0.69
a6	-0.04	0.17
a7	0.01	0.07
a8	0.01	0.17
a9	0	0
a10	-0.02	0.04

8.4 SEPARATION DIPOLES

The separation dipoles are used in several insertions to change the beam separation from the nominal 194 mm in the LHC arcs. In the experimental insertions the pair of D1-D2 dipoles brings the two beams onto a colliding orbit at the interaction point and then separates the beam again beyond the collision point. To reduce the beam-beam effects, the first separation dipole D1 is placed immediately upstream of the low-β triplet. In the high-luminosity insertions, high radiation levels are expected and more robust normal conducting magnets, MBXW, are used. In the ALICE and LHCb insertions, D1 is a stronger superconducting magnet, MBX, allowing more space for the injection systems. In all cases, the D2 separation dipole, MBRC, is a twin-aperture superconducting magnet. In the cleaning insertions, the pair of D3-D4 dipoles separates the beams to 224 mm to accommodate the collimation system, while in the RF insertion the beam separation is 420 mm so that individual RF cavities can be installed for each beam. The radiation levels in the cleaning insertions require the use of normal conducting dipoles, MBW (both for D3 and D4), while superconducting dipoles, MBRB (D4) and MBRS (D3), are used in the RF insertion.

8.4.1 Superconducting Separation Dipoles

The MBX (D1), MBRB/C (D4/D2) and MBRS (D3) dipoles are designed and built by BNL (USA) on the basis of the RHIC lattice dipole [7]. The MBX magnets are designed with one RHIC-style cold mass in a RHIC-style cryostat and the MBRS magnets are designed with two such cold masses side-by-side in a common cryostat. The cold masses are built straight, without the 47 mm sagitta of the RHIC magnets. The MBRB and MBRC magnets are built with coils that are pre-stressed with stainless steel collars. These collared coils are assembled into yokes with common outside dimensions but with two aperture spacing, depending on the type. The main parameters of the magnets are given in Tab. 8.8.

Table 8.8: Main parameters of the MBX, MBRB/C and MBRS superconducting separation dipoles

Coil inner diameter Magnetic length Nominal field	80 mm 9.45 m 3.8 T
Operating temperature	1.9 K (MBX) 4.5 K (MBRB/C, MBRS)
Nominal current	5750 A (MBX, MBRS) 6050 A (MBRB/C)
Aperture separation	188 mm (MBRC) 194 mm (MBRB) 414 mm (MBRS)
Cold bore diameter OD/ID	78/74 mm (MBX) 73/69 mm (MBRB/C, MBRS)
Peak field in coil Quench field Stored energy per aperture Inductance per aperture	4.2 T 4.8 T 470 kJ 25.8 mH
Quench protection	Quench heaters, two independent circuits per aperture
Cable width Mid-thickness Keystone angle No of strands Strand diameter Cu/SC Ratio Filament diameter j_c	9.73 mm 1.166 1.2 deg. 30 0.648 mm 1.8 6 μm 2500 A/mm^2 (4.2 K and 5 T)
Mass	4500 kg (MBX) 13500 kg (MBRS) 24500 kg (MBRB/C)

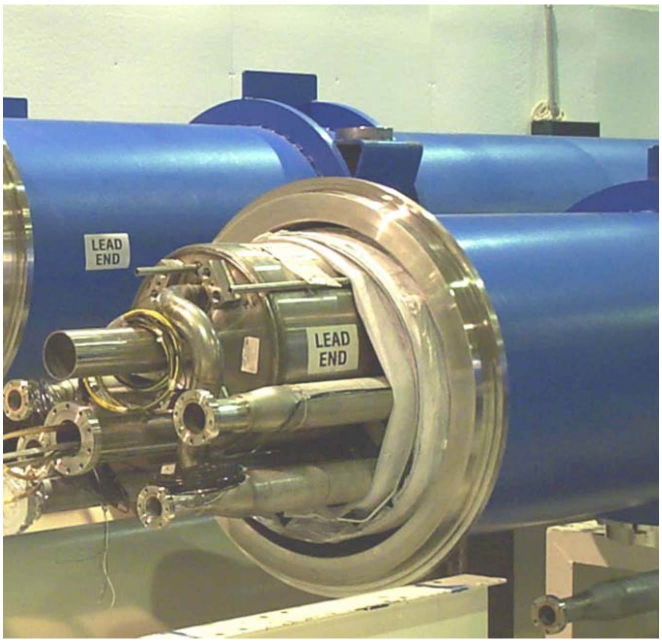


Figure 8.9: The MBX (D1) cryo-dipole, viewed from the lead end.

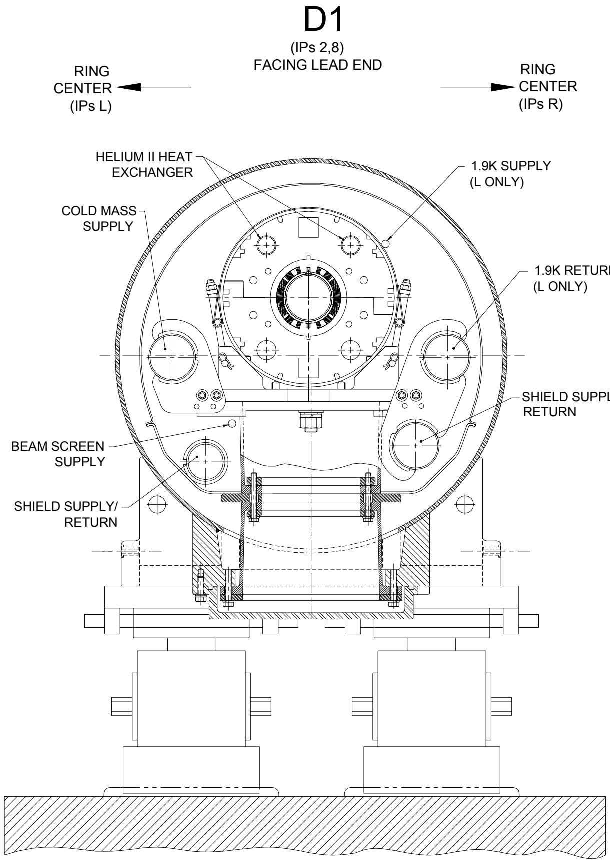


Figure 8.10: Cross-section of the MBX (D1) cryo-dipole, of same design as the RHIC main dipoles.

Table 8.9: Field quality of the MBX magnets at 3.8 T (units of 10^{-4} at 25 mm)

	Measured average		Reference Table <b> +- Δb			Measured rms	Reference σ(b)
b2	-0.19	+-0.24	0.25	+-0.79	b2	0.53	0.28
b3	-3.10	+-0.98	-1.71	+-3.57	b3	2.20	1.70
b4	0.14	+-0.08	0.07	+-0.21	b4	0.18	0.08
b5	0.99	+-0.17	0.24	+-0.80	b5	0.37	0.39
b6	0.030	+-0.036	-0.120	+-0.100	b6	0.080	0.040
b7	1.160	+-0.031	1.170	+-0.190	b7	0.070	0.100
b8	-0.010	+-0.009	-0.020	+-0.030	b8	0.020	0.010
b9	-0.070	+-0.013	0.010	+-0.120	b9	0.030	0.040
b10	0.040	+-0.009	0.040	+-0.050	b10	0.020	0.020
b11	-0.680	+-0.004	-0.600	+-0.040	b11	0.010	0.020

	Measured average		Reference Table <a> +- Δa			Measured rms	Reference σ(a)
a2	-3.16	+-1.02	0.54	+-3.71	a2	2.29	1.51
a3	-0.83	+-0.04	-1.31	+-0.55	a3	0.09	0.18
a4	-0.58	+-0.28	0.06	+-1.08	a4	0.62	0.41
a5	0.17	+-0.04	0.16	+-0.17	a5	0.10	0.06
a6	0.050	+-0.072	-0.050	+-0.550	a6	0.160	0.160
a7	-0.110	+-0.013	-0.110	+-0.060	a7	0.030	0.020
a8	0.050	+-0.013	-0.010	+-0.150	a8	0.030	0.050
a9	0.020	+-0.009	0.010	+-0.030	a9	0.020	0.010
a10	0.060	+-0.009	0.040	+-0.040	a10	0.020	0.020
a11	-0.010	+-0.004	-0.010	+-0.010	a11	0.010	0.010

MBX

The MBX dipole as seen from its lead end is shown in Fig. 8.9 and its cross-section is shown in Fig. 8.10. Many of its design features are identical to the RHIC main dipoles. However, the magnet is equipped with two heat exchangers allowing it to be cooled to 1.9 K and it has a larger cold bore (OD 78 mm) than the RHIC dipole. Another feature is the use of quench heaters as active protection elements. All these modifications require additional cryogenic and electrical instrumentation, described in [8].

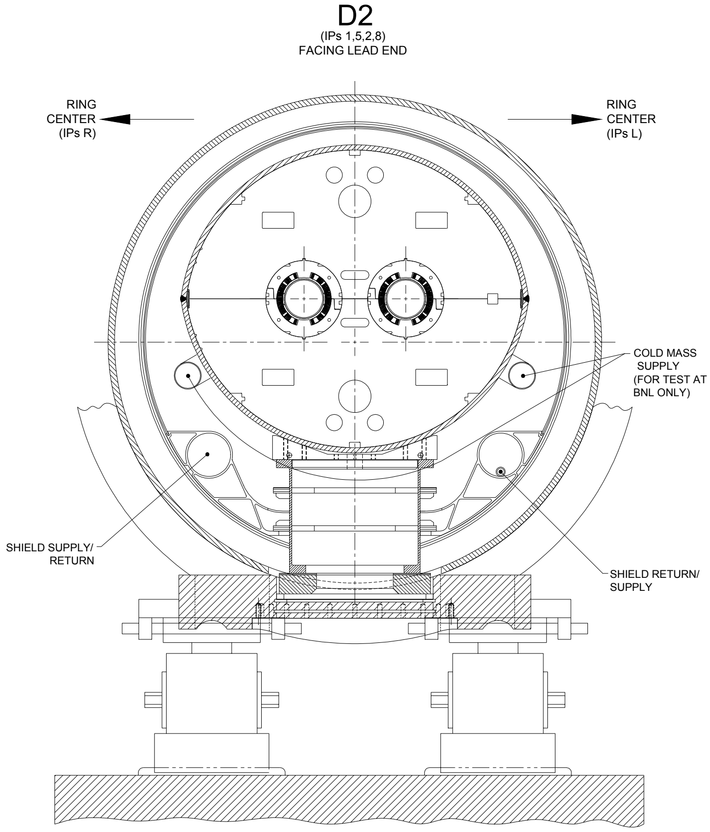


Figure 8.11: Cross section of the MBRC (D2) cryo-dipole at a support post location.

Figure 8.12: MBRB cryo-dipoles ready for shipment. The lower left unit is equipped with a QQS module.

BNL has completed all four MBX dipoles necessary for the LHC and an additional unit as a spare. All magnets were tested in BNL, including cold checkout and quench training at 4.5 K. All magnets were powered to well above the ultimate current at 4.5 K, leaving considerable margin for operation at 1.9 K in the LHC. One magnet was fully tested for static and dynamic field quality. The field quality of the other magnets was obtained on the basis of cold-warm correlations established during the RHIC production. The field quality of the as-produced magnets is compared in Tab. 8.9 to the reference field error table [9].

Table 8.10: Field quality of the MBRB/C dipoles at 3.8 T (units of 10^{-4} at 25 mm)

	Measured average	Reference Table <b> +- Δb		Measured rms	Reference σ(b)
b2	-0.18 +-0.10	-0.07 +-0.79	b2	0.36	0.28
b3	-0.49 +-0.39	1.99 +-3.57	b3	1.36	1.70
b4	0.07 +-0.10	-0.21 +-0.21	b4	0.35	0.08
b5	0.05 +-0.10	0.04 +-0.80	b5	0.34	0.39
b6	-0.006 +-0.042	-0.050 +-0.100	b6	0.145	0.040
b7	0.179 +-0.024	0.060 +-0.190	b7	0.083	0.100
b8	-0.008 +-0.010	-0.010 +-0.030	b8	0.036	0.010
b9	-0.154 +-0.009	0.000 +-0.120	b9	0.033	0.040
b10	-0.001 +-0.004	0.030 +-0.050	b10	0.012	0.020
b11	-0.644 +-0.004	-0.560 +-0.040	b11	0.013	0.020
	Measured average	Reference Table <a> +- Δa		Measured rms	Reference σ(a)
a2	-0.65 +-0.38	0.55 +-3.71	a2	1.31	1.51
a3	-1.14 +-0.08	-1.07 +-0.55	a3	0.26	0.18
a4	0.04 +-0.19	0.06 +-1.08	a4	0.67	0.41
a5	0.17 +-0.02	0.19 +-0.17	a5	0.08	0.06
a6	0.070 +-0.059	0.000 +-0.550	a6	0.206	0.160
a7	-0.086 +-0.007	-0.110 +-0.060	a7	0.025	0.020
a8	0.020 +-0.015	-0.010 +-0.150	a8	0.052	0.050
a9	0.026 +-0.003	0.010 +-0.030	a9	0.009	0.010
a10	0.043 +-0.004	0.030 +-0.040	a10	0.013	0.020
a11	-0.002 +-0.002	-0.010 +-0.010	a11	0.006	0.010

MBRB and MBRC

The MBRB magnet is a two-in-one magnet with parallel fields in the two apertures. The MBRC is very similar in design (its cross-section is shown in Fig. 8.11) and differs only by the nominal aperture spacing (188 mm). In addition, to allow installation of the beam screens, the cold bore in MBRB is slightly off-centred on the IP side [10]. The cross-talk between parallel fields in the two apertures is reduced by additional iron around the median plane, resulting in an oval shape of the cold mass. Its outer dimensions are identical in the vertical plane to the LHC main dipole, so that standard LHC support posts and other cryostat elements are used in a 9.8 m long vacuum tank. The MBRB/C magnets are equipped with QQS service modules, Fig. 8.12, which provide cryogenic connections to the QRL for the 4.5 K operation of the Q4-D2 (Q5-D4) string of magnets, as described in [11].

BNL has completed the construction of eight MBRC and two MBRB magnets for installation in the LHC, as well as one spare of each type. All magnets were tested at 4.5 K in BNL and showed very good training behaviour. The field quality of nine magnets was measured extensively and warm-cold correlations established. The correlations were used for extrapolating the field quality of the spare magnets. The field quality of as-built magnets is compared in Tab. 8.10 to the reference field error table [9].

MBRS

The MBRS separation dipole consists of two MBX-like cold masses assembled in a 9.6 m long cryostat, as shown in Fig. 8.13. The cold masses are aligned to a separation of 414 mm using three transverse beams, connected to the upper plates of standard LHC dipole posts. Other cryostat elements are identical to MBRB. The magnet interfaces on the non-IP side with the QQS service module, which provides the connection to the cryogenics and powering services. On the IP side, provisions are made for interconnecting MBRS with the MSRU undulator [12].

Three MBRS magnets are built by BNL, two of which are installed in the RF insertion and one is a spare. All magnets are fully tested at 4.5 K, including field measurements. The field quality of the MBRS magnets follows closely that of MBX, as shown in Tab. 8.9.

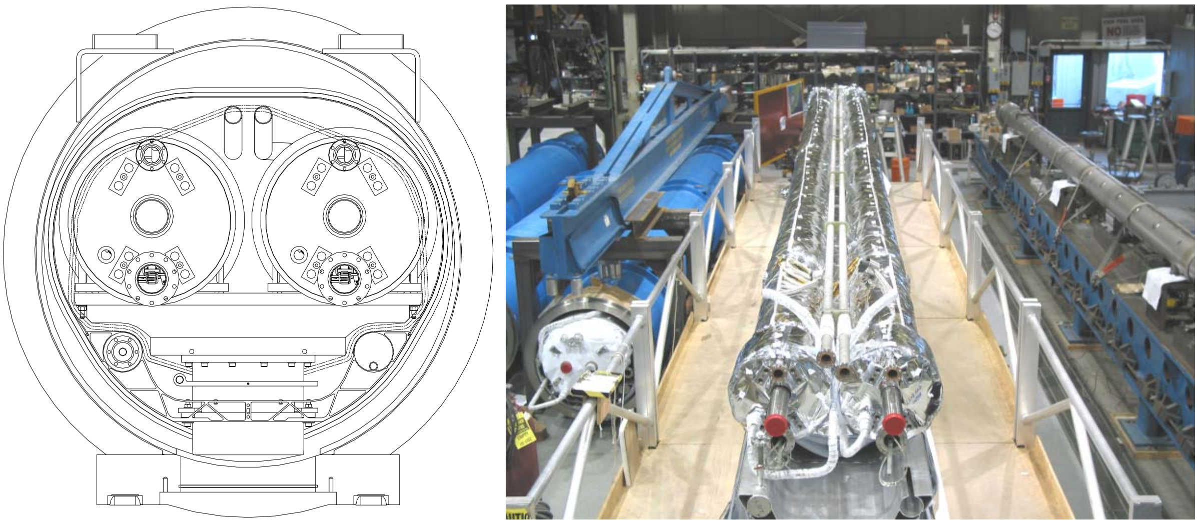


Figure 8.13: (Left) Cross-section of the MBRS dipole. (Right) Assembly of the MBRS cold masses at BNL.

8.4.2 Normal Conducting Separation Dipoles

The MBW and MBXW dipoles are designed and built by BINP (Novosibirsk, Russia) employing a well-established technology of epoxy-impregnated coils in a laminated window-frame steel yoke (Figs. 8.14, 8.15 and 8.16). The two coils of both types of magnet consist of three pancakes that are wound from a hollow rectangular copper conductor. The conductor is insulated with glass-fibre tape and impregnated with epoxy resin. The yoke is laminated from insulated magnetic steel sheets of 1.5 mm thickness to reduce eddy currents that are generated during ramping of the magnets. The laminations are held together by welded plates. The shape of the end-plates and shims is adjusted to compensate the magnetic end effect. The coils are fixed in the yoke by stainless steel clamps at the end of the magnet and further supported by separation blocks in the mid-plane. The magnets are manufactured as two half-cores that are clamped together with studs and nuts along the side cover plates. The main parameters of the magnets are given in Tab. 8.11.

The field quality of normal conducting magnets is defined by the shape of the steel poles. In order to guarantee good field quality, punching of laminations is controlled to within 0.05 mm in the vicinity of the apertures. Also, lamination stacks and the clamping of the two half-magnets are assembled within a tenth of a millimetre. Access to the laminations on the top and the sides of the magnet allows the verification of the magnet assembly after production. Specifications require a sag of less than 0.5 mm and a twist of less than 1 mrad. All these parameters are checked to assure the quality during production and to guarantee the required field quality. Magnetic field quality measured at BINP and at CERN is given in [13].

Table 8.11: Main parameters of the MBW and MBXW separation dipoles

Magnet type	**MBW**	**MBXW**
Magnetic length	3.4 m	
Beam separation	194-224 mm	0-27 mm
Gap height	52 mm	63 mm
Coil Protection temperature	< 65° C	
Nominal field	1.42 T	1.28 T
Nominal current	720 A	690 A
Inductance	180mH	145 mH
Resistance	55 mΩ	60 mΩ
Conductor X-section	18 x 15 mm²	
Cooling hole diameter	8 mm	
Number of turns per magnet	2 x 42	2 x 48
Minimum water flow	19 l/min	
Dissipated power at I_{nom}	29kW	29 kW
Mass	18000 kg	11500 g

MBW

The MBW magnet, Fig. 8.14, features a pole shape with varying gap height and two positions for the beam pipes (194 to 224 mm) while employing a standard H-type dipole construction. The two coils consist of three pancakes with 14 windings. The overall number of MBW magnets produced by BINP is 24, including 4 spares. The expected field quality is given in reference [14].

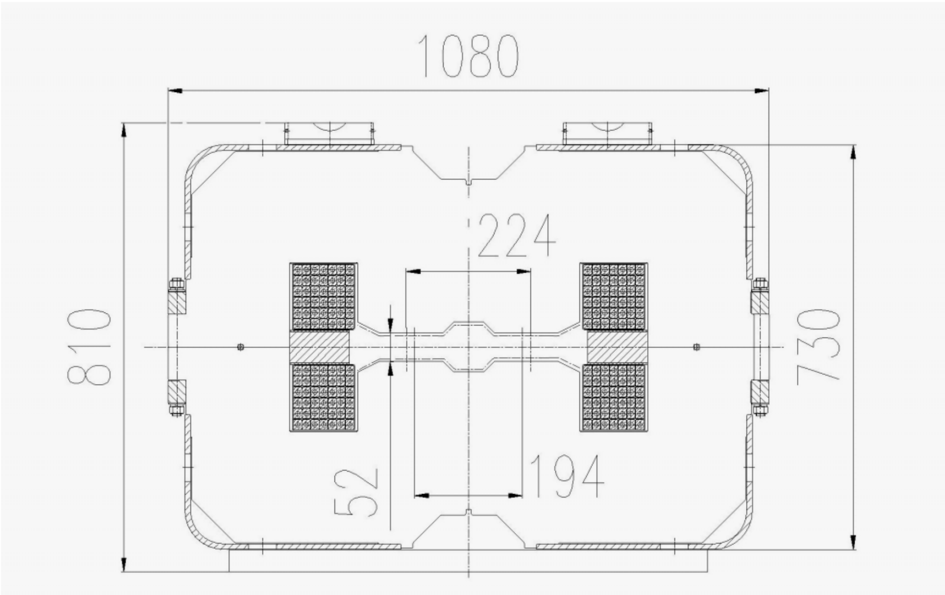


Figure 8.14: Cross-section of the normal conducting separation dipole MBW.

MBXW

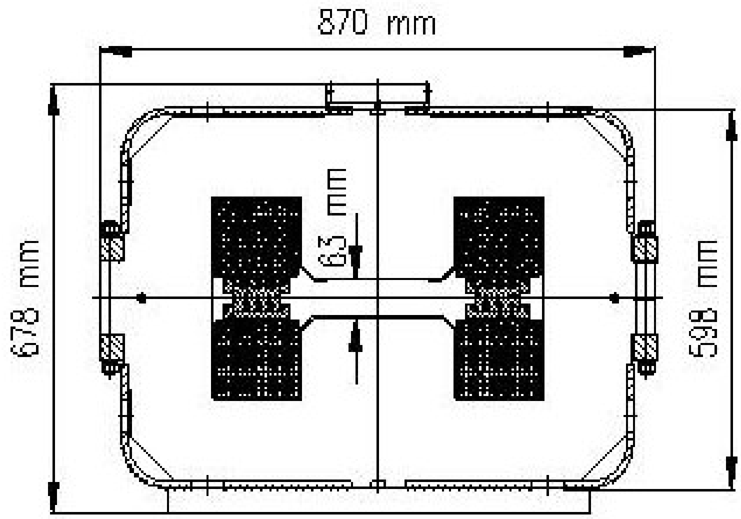


Fig. 8.15: Cross-section of the normal conducting separator dipole magnet MBXW.

The cross-section of the MBXW is shown in Fig. 8.15. It features a coil with three pancakes with 16 turns each, wound using the same copper conductor as for the MBW. Since both beams run through a single pipe, the pole region is 120 mm wide with a gap height of 63 mm. Small shims, placed along the sides of the pole, are part of the punched laminations and homogenize the field in the aperture. The total number of MBXW magnets built by BINP is 29, including 4 spares. A view of such a magnet seen from the connection end is shown in Fig. 8.16. The expected field quality is given in [15].

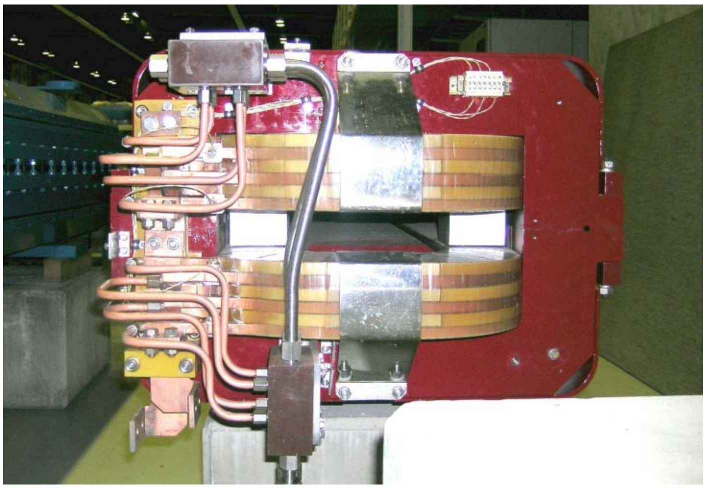


Figure 8.16: View of the connection end of the normal conducting separation dipole MBXW

8.5 LOW-BETA TRIPLETS

The low-β triplet, Fig. 8.17, is composed of four single-aperture quadrupoles with a coil aperture of 70 mm. The magnets are cooled with superfluid helium at 1.9 K using an external heat exchanger system capable of extracting up to 10 W/m of power deposited in the coils by the secondary particles emanating from the proton collisions. Two types of quadrupoles are used in the triplet, 6.6 m long MQXA magnets designed and developed by KEK (Japan) and 5.7 m long MQXB magnets designed and built by FNAL (USA). The magnets are powered in series with 7 kA, with an additional inner loop of 5 kA for the MQXB magnets. Together with the orbit correctors MCBX, skew quadrupoles MQSX and multipole spool pieces supplied by CERN, the low-β quadrupoles are completed in their cold masses and cryostated by FNAL. The cryogenic feed-boxes (DFBX), providing a link to the cryogenic distribution line and power converters, are designed and built by LBNL (USA).

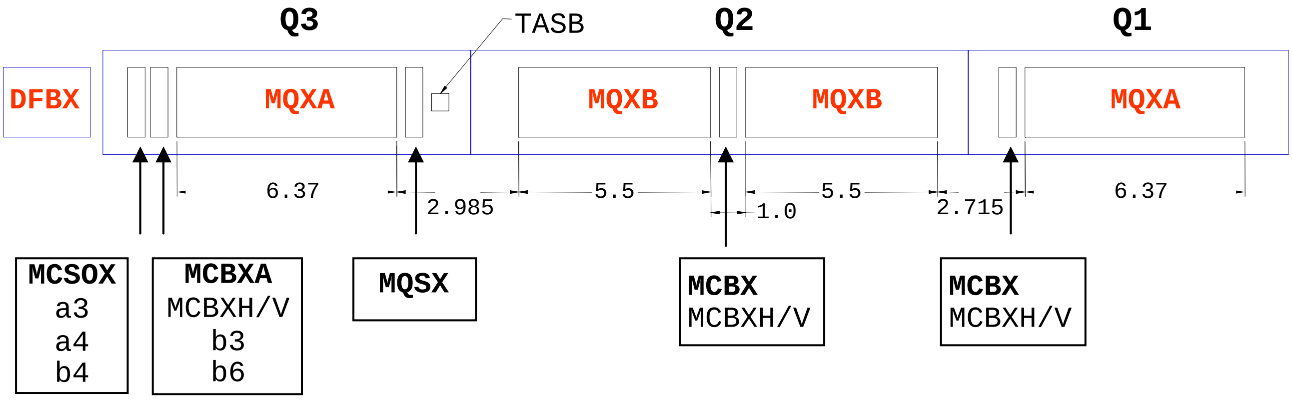


Figure 8.17: Schematic Layout of the low-β triplet.

Alongside the LHC main dipoles, the high-gradient, wide-aperture low-β quadrupoles are the most demanding magnets in the collider. They must operate reliably at 215 T/m, sustain extremely high heat loads in the coils and high radiation dose during their lifetime and have a very good field quality within the 63 mm aperture of the cold bore. In order to validate their design choices, KEK and FNAL have launched comprehensive R&D programmes comprising a number of short model magnets, [16] and [17]. Both programmes were successful in fulfilling the design goals and demonstrating the LHC operational requirements. An important result of the programmes, confirmed by the quadrupole prototypes, is that the field quality is considerably better than initially expected. As a result, the expected field error tables of the magnets were revised [18, 19] and the number and strength of the multipole correctors in the low-β triplet reduced and their arrangement simplified.

8.5.1 MQXA low-β Quadrupole

The design of the MQXA quadrupole is based on a four-layer coil using 11 mm wide Rutherford-type graded NbTi cables. The coils are wound and cured in two double layers and are assembled using 10 mm wide spacer-type collars, Fig. 8.18. The pre-stress in the coils and their rigidity is provided by the yoke structure, which consists of horizontally split laminations keyed at the mid-plane. The main parameters of the magnet are given in Tab. 8.12.

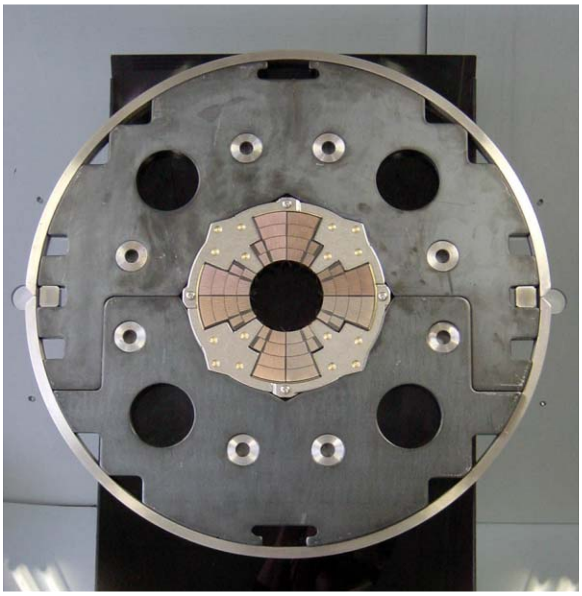


Figure 8.18: (Left) Cross-section of the MQXA low-β quadrupole. (Right) MQXA quadrupole ready for tests in the vertical cryostat in KEK.

Table 8.12: Main parameters of the MQXA low-β quadrupole

Coil inner diameter	70 mm
Magnetic length	6.37 m
Operating temperature	1.9 K
Nominal gradient	215 T/m
Nominal current	7149 A
Cold bore diameter OD/ID	66.5/62.9 mm
Peak field in coil	8.6 T
Quench field	10.7 T
Stored energy	2300 kJ
Inductance	90.1 mH
Quench protection	Quench heaters, two independent circuits
Cable width, cable 1/2	11/11 mm
Mid-thickness, cable 1/2	1.487/1.340 mm
Keystone angle, cable 1/2	2.309/1.319 deg.
No of strands, cable 1/2	27/30
Strand diameter, cable 1/2	0.815/0.735 mm
Cu/SC Ratio, cable 1/2	1.2/1.9
Filament diameter, cable 1/2	10/10 μm
j_c, cable1/2, (4.2 K and 6 T)	2200/2160 A/mm^2
Mass	9600 kg

KEK has completed the production of the total of 16 MQXA magnets, for eight Q1 and eight Q3 quadrupoles. In addition, two magnets have been built as spares. All magnets have been tested in the vertical testing facility in KEK, Fig. 8.18. The magnets were systematically trained to 230 T/m, well above the ultimate gradient in the LHC, to guarantee the temperature margin. The acceptance criterion was that following training and a full-energy dump, the magnets should be powered to 225 T/m without quench. All magnets passed this criterion. In addition to training, all magnets were systematically measured for static and dynamic field effects. The field quality of the production is given in Tab. 8.13, where reference values are also shown [18].

Table 8.13: Field quality of the MQXA low-β quadrupole at 205 T/m (units of 10^{-4} at 17 mm).

	Measured average	Reference Table <b> ± Δb		Measured rms	Reference σ(b)
b3	0.040 ± 0.080	0.000 ± 0.680	b3	0.330	0.096
b4	1.290 ± 0.030	-0.170 ± 0.920	b4	0.100	0.066
b5	-0.010 ± 0.010	0.000 ± 0.130	b5	0.040	0.250
b6	0.350 ± 0.020	0.330 ± 0.890	b6	0.090	0.440
b7	-0.002 ± 0.002	0.000 ± 0.031	b7	0.009	0.055
b8	0.022 ± 0.001	0.003 ± 0.041	b8	0.003	0.028
b9	-0.001 ± 0.002	0.000 ± 0.012	b9	0.008	0.019
b10	-0.016 ± 0.002	-0.002 ± 0.058	b10	0.007	0.037

	Measured average	Reference Table <a> ± Δa		Measured rms	Reference σ(a)
a3	0.220 ± 0.090	0.000 ± 0.680	a3	0.330	0.096
a4	-0.010 ± 0.080	0.000 ± 0.330	a4	0.290	0.510
a5	0.010 ± 0.010	0.000 ± 0.130	a5	0.040	0.240
a6	-0.020 ± 0.010	0.000 ± 0.070	a6	0.020	0.120
a7	0.002 ± 0.002	0.000 ± 0.031	a7	0.007	0.055
a8	0.001 ± 0.004	0.000 ± 0.021	a8	0.014	0.028
a9	-0.001 ± 0.001	0.000 ± 0.012	a9	0.004	0.019
a10	-0.004 ± 0.001	0.000 ± 0.012	a10	0.003	0.009

8.5.2 MQXB low-β Quadrupole

The MQXB design features a two-layer coil, with each layer individually wound using a 15.4 mm wide Rutherford-type NbTi cable, Fig. 8.19. The coils are assembled using free-standing collars, which provide the pre-stress and counteract the magnetic forces. The collared assembly is aligned in the yoke structure with precision keys and the magnet enclosed in a stainless steel helium vessel consisting of half-shells welded at the pole plane. The design parameters of the magnet are given in Tab. 8.14.

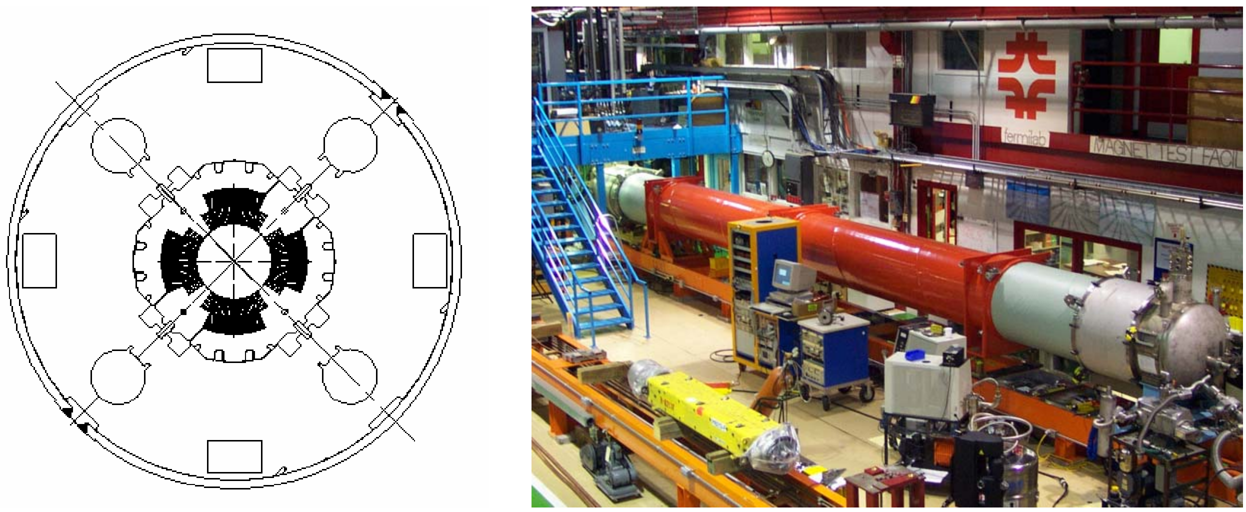


Figure 8.19: (Left) Cross-section of the MQXB low-β quadrupole. (Right) Q2 quadrupole on test in FNAL.

Table 8.14: Main parameters of the MQXB low-β quadrupole

Coil inner diameter	70 mm
Magnetic length	5.5 m
Operating temperature	1.9 K
Nominal gradient	215 T/m
Nominal current	11950 A
Cold bore diameter OD/ID	66.5/62.9 mm
Peak field in coil	7.7 T
Quench field	9.2 T
Stored energy	1360 kJ
Inductance	19.1 mH
Quench protection	Quench heaters, two independent circuits
Cable width, cable 1/2	15.4/15.4 mm
Mid-thickness, cable 1/2	1.456/1.146 mm
Keystone angle, cable 1/2	1.079/0.707 deg.
No of strands, cable 1/2	37/46
Strand diameter, cable 1/2	0.808/0.650 mm
Cu/SC Ratio, cable 1/2	1.3/1.8
Filament diameter, cable 1/2	6/6 μm
j_c, cable 1/2 (4.2 K and 5 T)	2750/2750 A/mm2
Mass	5700 kg

In total, 18 MQXB magnets are built by FNAL for the nine Q2 assemblies, one of which is a spare. FNAL tests all quadrupoles as cryostated magnets in a horizontal test stand, as shown in Fig. 8.19. Like the MQXA magnets, all quadrupoles are trained to 230 T/m at 1.9 K to guarantee ultimate gradient in LHC in presence of dynamic heat load induced by beam collisions. The quadrupoles are also tested for field quality and alignment. On the basis of the first half of production, a comparison of the measured and expected field multipoles is given in Tab. 8.15.

Table 8.15: Field quality of the MQXB low-β quadrupole at 205 T/m (units of 10^{-4} at 17 mm)

	Measured average		Reference Table <b> +- Δb			Measured rms	Reference σ(b)
b3	0.68	+-0.12	0.00	+-0.64	b3	0.27	0.25
b4	0.13	+-0.22	0.00	+-0.22	b4	0.49	0.25
b5	0.02	+-0.04	0.00	+-0.18	b5	0.08	0.10
b6	-0.16	+-0.13	0.21	+-0.42	b6	0.29	0.17
b7	-0.012	+-0.012	0.000	+-0.048	b7	0.027	0.018
b8	0.007	+-0.007	0.000	+-0.011	b8	0.015	0.017
b9	0.018	+-0.016	0.000	+-0.008	b9	0.036	0.009
b10	-0.015	+-0.005	-0.007	+-0.011	b10	0.012	0.009

	Measured average		Reference Table <a> +- Δa			Measured rms	Reference σ(a)
a3	-0.57	+-0.29	0.00	+-0.32	a3	0.65	0.25
a4	0.06	+-0.13	0.00	+-0.27	a4	0.29	0.25
a5	-0.35	+-0.11	0.00	+-0.18	a5	0.24	0.10
a6	0.02	+-0.03	-0.03	+-0.09	a6	0.06	0.17
a7	0.007	+-0.017	0.000	+-0.040	a7	0.039	0.018
a8	0.005	+-0.011	0.000	+-0.011	a8	0.025	0.017
a9	-0.032	+-0.009	0.000	+-0.008	a9	0.020	0.009
a10	-0.026	+-0.015	0.000	+-0.008	a10	0.034	0.009

8.5.3 Inner Triplet Cold Masses and Cryostats

The MQXA and MQXB magnets are completed with MCBX, MQSX and higher-order correctors to form the Q1, Q2 and Q3 quadrupoles. The Q1 quadrupole houses an MQXA and a single MCBX orbit corrector on the non-IP side, while the Q2 quadrupole includes two MQXB magnets with an MCBX corrector in between. The Q3 quadrupole has an MQXA and a skew quadrupole MQSX on the IP side and on the non-IP side an MCBX orbit corrector with a b_3-b_6 insert (MCSTX), followed by the a_3-a_4-b_4 (MCSOX) assembly.

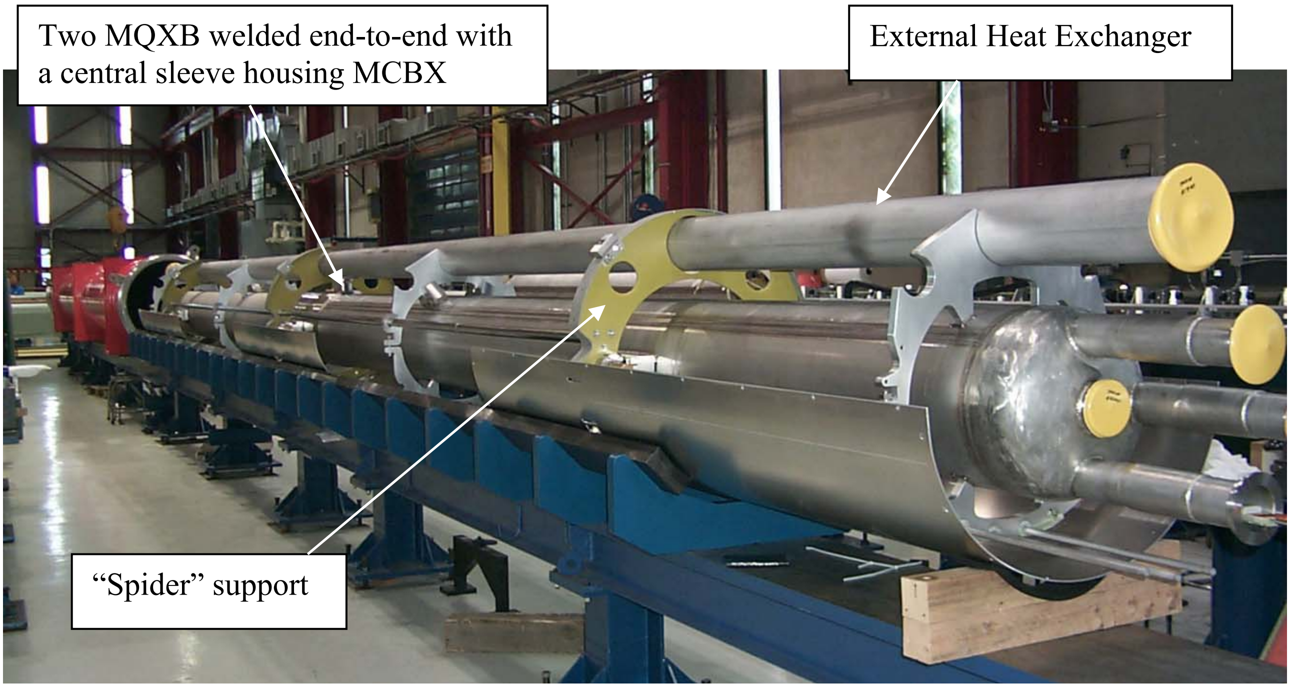


Figure 8.20: Q2 cryo-magnet assembly.

The high heat load expected in the high-luminosity insertions and the alignment requirements for the quadrupole positioning determined the design of the inner triplet cryostat [20]. The positioning of the cold mass and its stability is assured by a system of ring supports ("spiders"), locked to the reinforcements of the 914 mm diameter vacuum vessel, as shown in Fig. 8.20. Two spiders are used in Q1 and Q3 quadrupoles, which are 7.7 m and 8.4 m long, while the 12.5 m long Q2 quadrupole is supported with three spiders. The spiders also serve to guide the cryogenic pipes, in particular the external heat exchanger, which runs above the quadrupole cold masses. It also serves as an adapting element to slightly different outer dimensions of the MQXA and MQXB magnets.

The interconnections between inner triplet cryo-magnets are determined on the basis of power deposition and optics studies and consist of two long drift spaces in between Q1-Q2 and Q2-Q3 and a short interconnect Q3-DFBX. The longitudinal space in-between Q1-Q2 and Q2-Q3 is used for mounting a beam position monitor BPMS and an additional absorber, TASB. The design of interconnecting elements and absorbers takes into account the cooling and beam vacuum requirements of the long drift tubes and the constraints of mounting on the test bench and in the tunnel.

8.6 ORBIT AND MULTIPOLE CORRECTORS IN THE INSERTIONS

Most of the corrector magnets in the insertions are superconducting, except the corrector magnets in the cleaning insertions associated with Q4 and Q5 which are normal conducting magnets of type MCBW (see Sec. 8.6.3). The general design and fabrication principles of the superconducting correctors of the insertions [21] are similar to those of the arcs and are made also from similar strands as described in Sec. 7.6. The list of the superconducting correctors used in the insertions is given in Tab. 8.16.

Table 8.16: Overview of superconducting corrector magnet in the insertions.

Name	Description	Location
MCBC, MCBY	Dipole orbit correctors	Dispersion suppressors & matching sections
MQTL	Long trim quadrupole	Dispersion suppressors & matching sections
MCBX	Nested horizontal & vertical dipole orbit corrector.	Inner Triplets
MCBXA= MCBX+MCSTX	MCBX with a nested 6-pole, 12-pole multipole corrector insert	
MQSX	Skew quadrupole	Inner Triplets
MCOSX+MCOX +MCSSX	Nested skew sextupole, octupole, skew octupole corrector package	Inner Triplets

8.6.1 Orbit Correctors MCBC/Y and Long Trim Quadrupoles MQTL

MCBC and MCBY

The LHC insertion regions are equipped with 6 different types of twin-aperture dipole orbit corrector assemblies. The MCBC (four different types) and the MCBY (two different types) are twin-aperture assemblies consisting of two superconducting dipole modules mounted in a common support structure. These magnet modules are individually powered and arranged so that the field in one aperture is vertical (horizontal correction) and the other horizontal (vertical correction).

The MCBC assemblies are associated with MQM and MQ type quadrupoles, whereas the MCBY assemblies are associated with the MQY quadrupoles. Consequently, the modules of the MCBC assemblies have a 56 mm bore diameter whereas the MCBY modules have a 70 mm bore diameter. Both types of modules are of similar construction and dimensions, using the same superconducting wire. Since the MCBC assemblies are associated with two different types of quadrupoles, two versions of support structures are required, which differ in their outer contour and diameter. The MCBC correctors used in the MQM-type cold mass configuration, which is based on a welded half-shell design, have the same outer contour as the MQM quadrupoles. These correctors are either MCBCA or MCBCB types, depending on the orientation and polarity of their modules. The MCBC correctors used in the MQ-type cold mass configuration, based on the inertia tube design, have the same outer contour as the MSCB correctors (see Sec. 7.6.3). These correctors are either MCBCC or MCBCD, depending on orientation and polarity of their modules. The MCBY correctors are used in the MQY cold mass configuration, which is based on the welded half-shell design and therefore has the same outer contour as the MQM quadrupoles. The main parameters of MCBC and MCBY orbit correctors are shown in Tab. 8.17 and their cross-sections are shown in Fig. 8.21.

Table 8.17: Main parameters of the MCBC and MCBY orbit correctors.

	MCBC	MCBY
Coil inner diameter	56 mm	70 mm
Magnetic length	0.904 m	0.899 m
Operating temperature	1.9 K	1.9/4.5 K
Nominal field (at 1.9/4.5 K)	3.11/2.33 T	3.00/2.50 T
Nominal current (at 1.9/4.5 K)	100/74 A	88/72 A
Peak field in coil (at 1.9/4.5 K)	3.65/2.68 T	3.60/2.96 T
Superconductor	Type 2	Type 2
Theoretical quench current (at 1.9/4.2 K)	172/127 A	162/120 A
Stored energy (at 1.9 K)	14.2 kJ	13.6 kJ
Self inductance	2.84 H	5.27 H
DC resistance (RT)	375 Ω	501 Ω
Overall length	1100 mm	1100 mm
Outer diameter of assembly	452 mm	475 mm
Magnet module mass	203 kg	193 kg
Total mass including the support structure	1234 kg	1247 kg

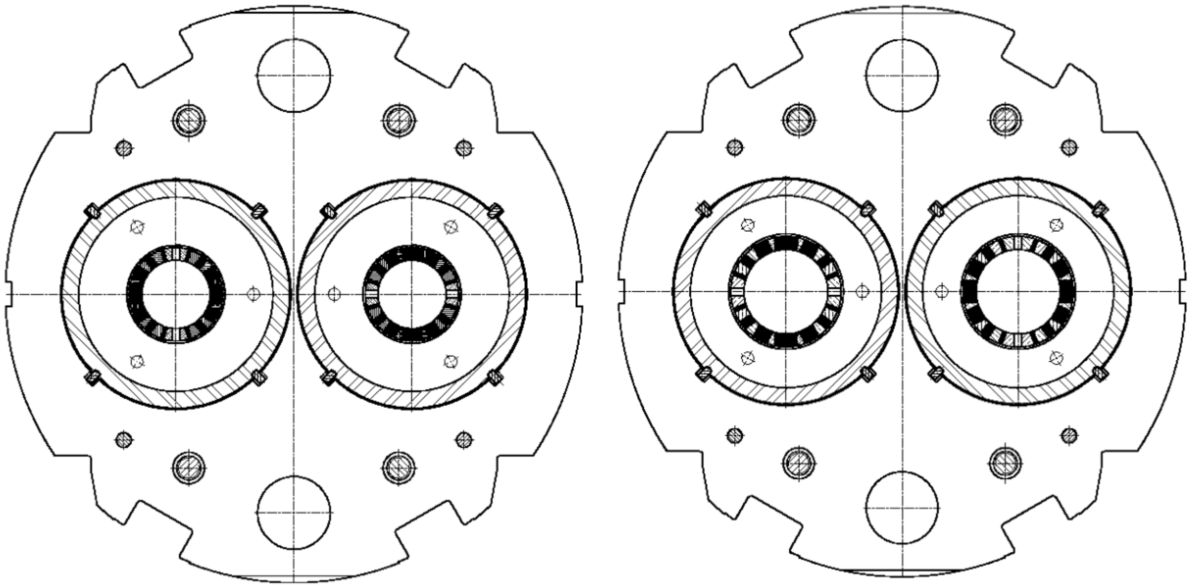


Figure 8.21: Cross-section of MCBC (left) and MCBY (right).

Each dipole module consists of two vacuum impregnated dipole coils, a laminated iron yoke, aluminium shrinking cylinders and an end plate, which supports the electrical connections. The superconducting wire has a rectangular cross-section and is enamel insulated. The dipole coils are made by winding either 14 (MCBC) or 15 (MCBY) such wires, pre-assembled as a flat ribbon, around a copper central post with composite end-spacers. The individual wires of the flat ribbon are connected in series on the end plate. All interconnections are done by soft soldering.

Pre-compression is applied to the coils by shrink fitting an aluminium cylinder over the steel laminations that make up the yoke [22]. The pre-compression is determined by the interference fit between the aluminium shrink ring and the yoke laminations around the coils. The end plate provides the reference for an accurate machining of the keyways along the outer diameter of the shrinking cylinder, which accurately locate the modules precisely within the twin-aperture support structure. The support structure is assembled from stacked steel laminations dowelled together and locked in position with tie-rods between thick steel end plates

MQTL

Each long trim quadrupole assembly consists of a pair of single-aperture quadrupole modules mounted in a twin-aperture support structure. They are used to tune the optical parameters of a certain number of quadrupoles in the dispersion suppressors and matching sections. In the dispersion suppressors one MQTL is placed alongside the MQ quadrupole in all Q11. In addition, in IR3 and IR7 one MQTL is placed alongside the MQ quadrupole in Q7 to Q10, except in Q9, where two MQTL are used. In all these cases, the MQTL assemblies are mounted in an inertia-tube type cold mass and their common support structure has the outer contour of the MSCB correctors (see Sec. 7.6.3). Further, the Q6 quadrupoles in IR3 and IR7 consists of six MQTL mounted together in a half-shell type cold mass and the common support structure has the same outer contour as the MQM. Consequently, the MQTL have two types of support structures, MQTLI for the inertia-tube type and MQTLH for the half-shell type, as shown in Fig 8.22. Both types of assemblies use the same single-aperture modules, MQTLC. The design parameters of the MQTLH and MQTLI quadrupoles are given in Tab. 8.18.

Each magnet module (MQTLC) consists of four epoxy vacuum-impregnated coils, a laminated iron yoke, an aluminium shrinking cylinder in six sections and an end plate that supports the electrical connections. The superconducting wire has a rectangular cross-section and is enamel insulated. The coils are made by counter-winding three such wires, pre-assembled as a flat ribbon, around a G11 central post with composite end spacers and subsequently wrapped with a glass-fibre/epoxy bandage. The module and final magnet assembly is similar to the MCBC and MCBY corrector magnets. The coil inter-connections are made by ultrasonic welding. Quench protection resistors are connected in parallel with each module and mounted on the support-structure end plate at the connection end of the magnet assembly.

Table 8.18: Main parameters of the MQTL corrector magnets

	MQTLH	**MQTLI**
Coil inner diameter	56 mm	
Magnetic length	1300 mm	
Operating temperature	4.3 K	1.9 K
Nominal gradient	129.4 T/m	
Nominal current	550 A	
Peak field in coil	4.1 T	
Superconductor type	3	
Theoretical quench current at 4.2 K/1.9 K	670/945 A	
Stored energy	18.15 kJ	
Self inductance	0.12 H	
Overall length	1400 mm	
Module mass	95 kg	
Mass including the twin aperture support structure	1850 kg	1250 kg

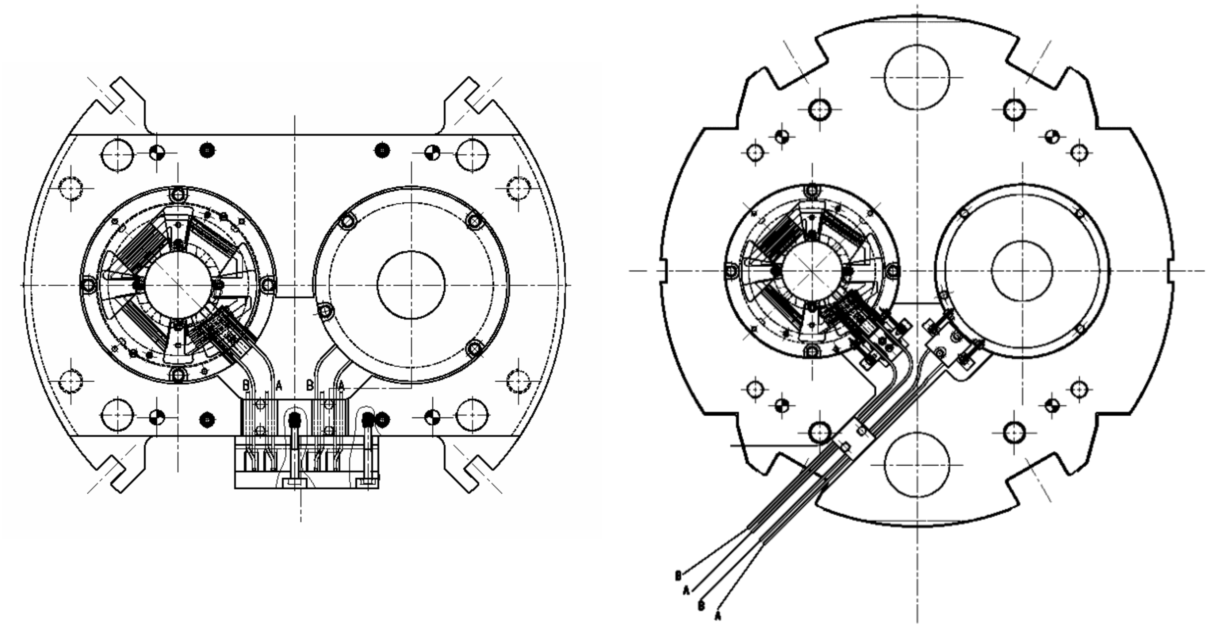


Figure 8.22: MQTLH cross-section (left) and MQTLI cross-section (right).

8.6.2 Correctors for the Inner Triplet

MCBX

Each of the eight inner triplets of the LHC is equipped with three combined horizontal and vertical correction dipoles for closed orbit correction [23]. The MCBX have nested coils and a single-aperture of 90 mm bore diameter, thus providing space for the MCSTX insert. The MCBX magnets are flanged to the end plate of the high-gradient inner triplet quadrupoles (MQXA and MQXB). The main parameters of the MCBX are shown in Tab. 8.19 and the cross-section in Fig. 8.23.

The MCBX magnet consists of two nested dipole coil layers, surrounded by an aluminium shrinking cylinder, a laminated iron yoke, a stainless steel outer shell and an end plate, which supports the electrical connections. The superconducting wire has a rectangular cross-section and is enamel insulated. The dipole coils are made by winding eight superconducting wires, pre-assembled as a flat ribbon, around a copper central post with composite end-spacers. The coils are individually vacuum impregnated with epoxy. The completed coil assembly consisting of two coil layers and a dry glass-fibre bandage is again vacuum impregnated with epoxy to provide sufficient mechanical strength to resist the shear forces arising from the combined excitation of the horizontal and vertical dipoles.

Table 8.19 Main parameters of MCBX inner triplet orbit corrector.

	MCBXV	MCBXH
Coil inner diameter	90 mm	120.8 mm
Magnetic length	0.48 m	0.45 m
Operating temperature	1.9 K	
Nominal field	3.26 T	3.35 T
Nominal current	550 A	
Turns per coil	360	440
Peak field	3.71 T	4.02 T
Superconductor type	4	4
Theoretical quench current at 1.9 K	1240 A	1175 A
Stored energy	26.5 kJ	43.4 kJ
Self inductance	175.2 mH	287.2 mH
Overall length	730 mm	
Outer diameter of assembly	350 mm	
Aperture	90 mm	
Mass	465 kg	

Precompression is applied to the coils by shrink fitting of the aluminium cylinder over the coil assembly. The magnitude of the pre-compression is mainly determined by the interference fit between the aluminium shrinking cylinder and the coil assembly. The iron yoke, which is made of steel laminations surrounded by a stainless steel outer shell, centres the coil assembly and provides support against the electromagnetic forces. The magnetic performance of a MCBX prototype magnet is described in [24].

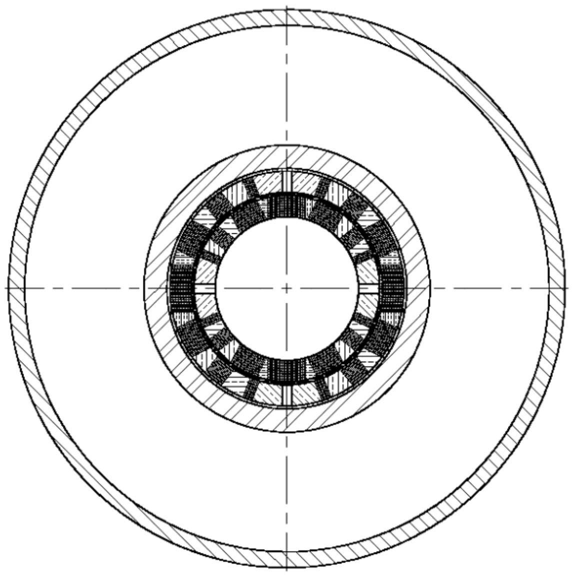


Figure 8.23: MCBX cross-section, without MCSTX insert.

MCSTX Corrector Package

One MCBX corrector in each inner triplet houses an MCSTX corrector magnet inside its aperture. The MCSTX insert consist of a nested superconducting sextupole (MCSX) and dodecapole (MCTX) windings. These single-aperture inserts have inner and outer bore diameters of 70 and 89 mm, respectively. The MCBX correctors mounted with a MCSTX corrector package are designated as MCBXA. The design parameters of MCSTX are given in Tab. 8.20.

Table 8.20: Main parameters of b_3 and b_6 windings of the MCSTX corrector package insert.

	MCTX		**MCSX**	
Nominal field at 17 mm radius	0.0103 T		0.015 T	
Magnetic length	0.615 m		0.576 m	
Operating temperature	1.9 K			
Nominal operation current	80 A		50 A	
Turns per coil	128		36	
No of coils	6		6	
Peak field in coils	4.1 T	1)	4.2 T	1)
Superconductor type	2		2	
Theoretical quench current at 1.9 K	208 A	1)	220 A	1)
Theoretical quench current at 1.9 K	294 A	2)	325 A	2)
Stored energy at nominal current	93.6 J		5.9 J	
Self inductance	29.2 mH		4.7 mH	
Inner diameter of insert	70 mm			
Outer diameter of insert	89.5 mm			
Total mass (approx.)	4 kg			

1) With background field of 3.9 T from the MCBX

2) Individual powering

The MCSTX insert consists of two nested coil layers (sextupole and dodecapole), a composite support tube, an aluminium outer shell and end plates which support the electrical connections. The superconducting wire has a rectangular cross-section and is enamel insulated. The dodecapole coils are made by counter-winding two superconducting wires, pre-assembled as a flat ribbon, around a copper central post. The sextupole coils are wound as a single layer around a composite central post. Each coil is impregnated with epoxy and subsequently cured.

The insert is assembled into the bore of the MCBX with its connection plate dowelled to the end plate of the MCBX. At the non-connection end the insert is centred by means of an aluminium disc fitted to the return end of the MCBX coil assembly.

MQSX

Table 8.21: Main parameters of the inner triplet skew quadrupole corrector MQSX

	MQSX
Coil inner diameter	70 mm
Magnetic length	0.223 m
Operating temperature	1.9 K
Nominal gradient	80 T/m
Nominal current	550 A
Peak field in coil	3.94 T
Superconductor	Type 3
Theoretical quench current	926 A
Stored energy	2116 J
Self inductance	14.0 mH
Overall length	300 mm
Total mass (approx.)	50 kg

Each inner triplet houses a skew quadrupole corrector, MQSX. The MQSX assemblies are flanged to the end of an inner triplet quadrupole MQXB. The main design parameters of this corrector magnet are given in Tab. 8.21.

The MQSX magnet assembly consists of four coils, a laminated iron yoke, a stainless steel outer shell and end plates which support the electrical connections. The superconducting wire has a rectangular cross-section and is enamel insulated. The coils are made by counter-winding two such wires, pre-assembled as a flat ribbon, around a composite epoxy central post. Each coil is impregnated with epoxy and cured. The end plate supports the electrical connections and provides a reference for the angular alignment of the magnet assembly. Coil inter-connections are soft-soldered.

Pre-compression is applied to the coils by shrink fitting a stainless steel outer shell over the yoke laminations. The pre-compression is determined by the interference fit between the outer shell and the yoke laminations around the coils.

MCSOX Corrector Package

Each inner triplet houses a combined corrector magnet package of type MCSOX. It comprises a nested skew octupole (MCOSX), an octupole (MCOX) and a skew sextupole (MCSSX) magnet [25]. This assembly is flanged to the end of the MCBXA corrector. The main design parameters of the MCSOX corrector package are given in Tab. 8.22.

Table 8.22: Design parameters of the inner triplet corrector package, MCSOX.

	MCOSX	MCOX	MCSSX
Bore diameter of assembly		70 mm	
Magnetic length	0.138 m	0.137 m	0.132 m
Operating temperature		1.9 K	
Nominal field at 17 mm radius	0.0475 T	0.0453 T	0.1089 T
Nominal current	100 A	100 A	100 A
Peak field in coils	1.34 T	1.37 T	1.32 T
Superconductor		Type 2	
Theoretical quench current at 1.9 K	267 [1)]	262 [1)]	257 [1)]
Stored energy	15.9 J	21.8 J	38.8 J
Self inductance	3.2 mH	4.4 mH	7.8 mH
Overall length		175 mm	
Total mass (approx.)		30 kg	

[1)] With two other layers powered at the nominal current

The MCSOX corrector package consists of the three nested winding layers mentioned above, a laminated iron yoke, a stainless steel outer shell and an end plate. The superconducting wire has a rectangular cross-section and is enamel insulated. The three types of coils are made by counter-winding a single superconducting wire around a composite epoxy central post. Each coil is impregnated with epoxy and subsequently cured. The end plate supports the coil interconnections and also provides a reference for the angular alignment of the magnet assembly. The coil inter-connections are soft-soldered.

Pre-compression is applied to the coils by shrink fitting the stainless steel outer shell over the eccentric steel laminations that make up the yoke. The pre-compression is determined by the interference fit between the outer shell and the yoke laminations around the coils.

Table 8.23: Main parameters of the MCBW normal conducting correction dipoles.

Magnet type	MCBW
Magnetic length	1.7 m
Beam separation	224 mm
Gap Height	52 mm
Coil Protection temperature	<65° C
Nominal field	1.1 T
Nominal current	550 A
Inductance	50 mH
Resistance	60 mΩ
Conductor X-section	16 x 10 mm²
Cooling hole diameter	5 mm
Number of turns per magnet	2 x 42
Minimum water flow	9 l/min
Dissipated power at I_{nom}	14 kW
Mass	4500 kg

8.6.3 Normal Conducting Orbit Correction Dipoles in IR3/7

The MCBW dipoles are designed and built by BINP (Novosibirsk, Russia). The MCBW dipoles come in two versions - MCBWH and MCBWV - as horizontal and vertical orbit corrector magnets, shown in Fig. 8.24. The magnet acts only on one beam, while the other passes through a passive aperture in the horizontal version and outside the magnet in the vertical version. The power and water distribution as well as the position of the supports and target holders are specific to each version, while the rest of the design is identical. A total of 20 MCBW corrector magnets are built including two spares of each type. A view from the end of a MCBWH is shown in Fig. 8.25. The main parameters of the MCBW magnet are given in Tab. 8.23. The construction and expected field quality are described in [26].

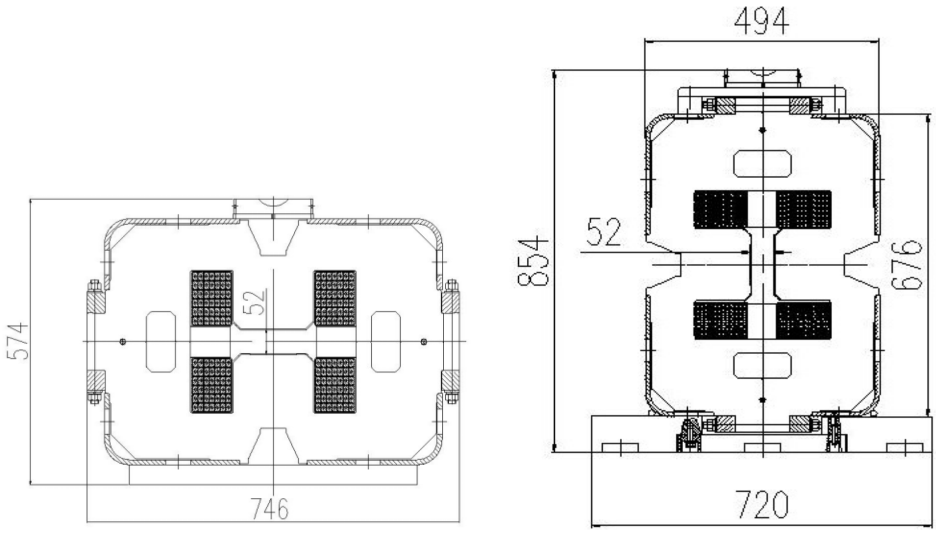


Figure 8.24: Cross section of the normal conducting orbit correction dipole MCBW in a horizontal (MCBWH) and in a vertical configuration (MCBWV).

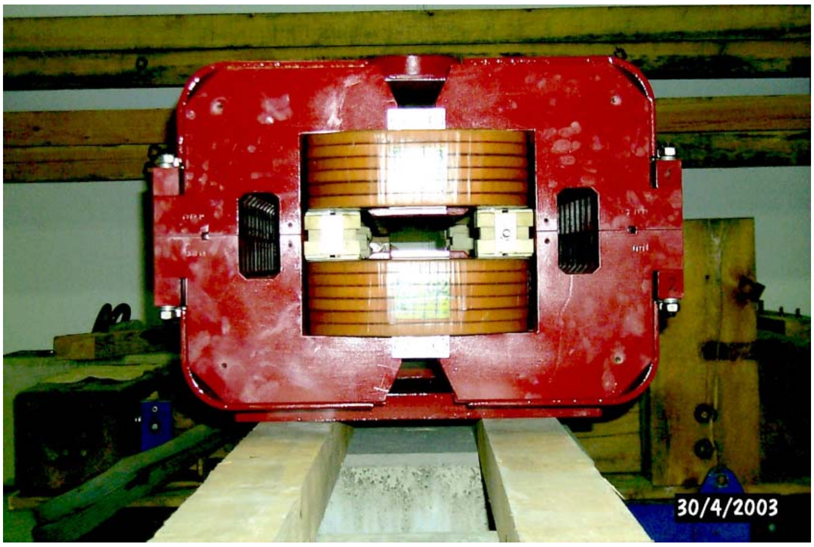


Figure 8.25: End view of the normal conducting orbit correction dipole MCBWH

8.7 COMPENSATOR DIPOLES IN ALICE AND LHCb EXPERIMENTS

The effect of spectrometer dipoles in ALICE (IR2) and LHCb (IR8) experiments on the beam is compensated in both cases with three dipoles, one placed symmetrically with respect to the IP and two weaker dipoles placed next to the inner triplets. The dipole field of the ALICE spectrometer, which produces a vertical kick on the beam, is compensated with a MBWMD and two MBXWT magnets. The MBWMD is a magnet from the SPS complex, originally built for the ISR beam lines (type HB2 turned vertical). Its main parameters are shown in Tab. 8.24 and its cross section is shown in Fig. 8.26. The LHCb dipole, which produces a horizontal kick on the beam, is compensated by an MBXWH magnet and two MBXWS magnets. The MBXWH is in fact an MBXW separation dipole, discussed in Section 8.4.2 and the MBXWT and MBXWS magnets are short versions of the MBXW dipole. The parameters of these magnets are given in Tab. 8.24. All MBXW type magnets are designed and built by BINP (Russia).

Table 8.24:Main parameters of the compensator dipoles for ALICE and LHCb. The magnets of the first three columns have all the same cross-section as MBXW.

Magnet type	**MBXWH**	**MBXWT**	**MBXWS**	**MBWMD**
Magnetic length	3.4 m	1.5 m	0.8 m	2.6 m
Gap height		63 mm		80 mm
Coil protection temperature		< 65º C		< 65º C
Nominal field	1.24 T	1.20 T	1.33 T	1.32 T
Current at nominal field	670 A	630 A	780 A	475 A
Inductance	145 mH	70 mH	35 mH	639 mH
Resistance	60 mΩ	40 mΩ	20 mΩ	172 mΩ
Conductor X-section		18 x 15 mm²		16.3 x 10.8 mm²
Cooling hole diameter		8 mm		6.6 mm
Number of turns per magnet		2 x 48		2 x 102
Minimum water flow	19 l/min	5 l/min	7 l/min	20 l/min
Dissipated power at I_{nom}	27 kW	16 kW	12 kW	39 kW
Mass	11500 kg	5800 kg	3700 kg	20500 kg

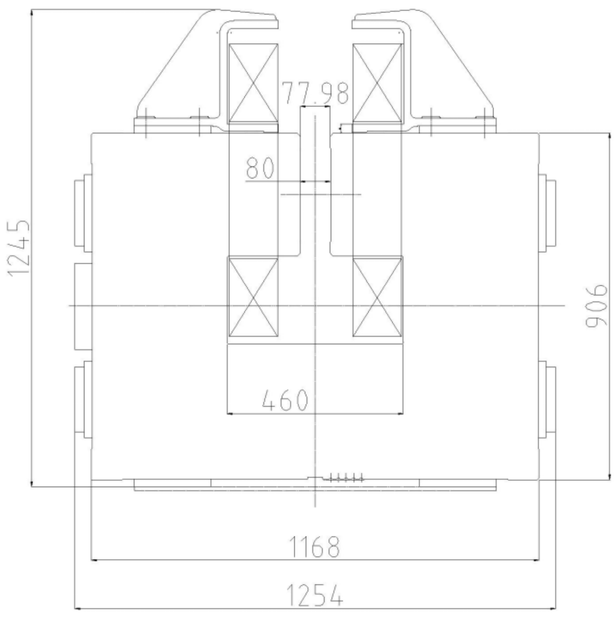


Fig. 8.26: Cross-section of the normal conducting compensation dipole MBWMD for ALICE.

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