Corrector Engineering Challenges and Issues

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1. Introduction

The inner triplets of the LHC will each house two combined horizontal and vertical correction dipoles, MCBX, and a skew quadrupole corrector, MQSX. Both magnet types will have enlarged apertures of 90 mm to create place for additional nested corrector windings. From the construction and performance point of view the MCBX will not have more than two corrector layers, whereas the lower background field of about 1.5 T in the MQSX allows the mounting of up to three multipole layers in it. This paper describes the MCBX orbit correctors and the experience obtained with the two prototypes, some aspects of the correction windings and their limitations, and the parameters of the future MQSX skew quadrupole.

2. Low-β Dipole Corrector MCBX

2.1. Design

The MCBX-magnet, whose main parameters are listed in Table I, features a horizontal dipole nested inside a vertical one. The coils of the 0.6 m long single-bore magnet are wound with 7 or 9 rectangular superconducting wires pre-assembled as flat cables. To create the required ampere-turns the individual wires are then connected in series on the end plate.

Table I: Main parameter of low-b dipole MCBX

	Horizontal dipole	Vertical dipole	
MAGNETICS			
Nominal strength	3.3	3.3	T
Integrated field	1.2	1.1	Tm
Magnetic length	0.37	0.34	m
Peak field in coil	4.4	4.8	T
GEOMETRY			
Overall length	0.55		m
Coil length	0.5	0.5	m
Coil inner diameter	90	123.7	mm
Coil outer diameter	119.7	146.8	mm
Yoke inner diameter	200/180[1]		mm
Yoke outer diameter	470/330[1]		
Overall outer diameter	500/350[1]		mm
ELECTRICS			
Nominal Current	0-511	0-599	A
Number of turns/coil	414	406	
Stored energy/magnet	17.9	25.2	kJ
Self inductance/magnet	0.137	0.140	H
CONDUCTOR			
Cross section	1.6	1.6	mm^2
Cross section(metal)	1.3	1.3	mm^2
Copper/NbTi ratio	1.6	1.6	
Filament diameter	10	10	µm
Twist pitch	18	18	mm
Current density (NbTi)	1022	1198	A/mm^2
Margin to quench	51.7	46.2	%

[1] First/second prototype magnet

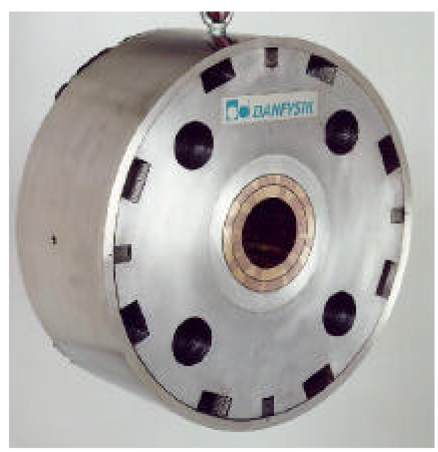

Figure 1: Mechanical model of the first MCBX prototype magnet

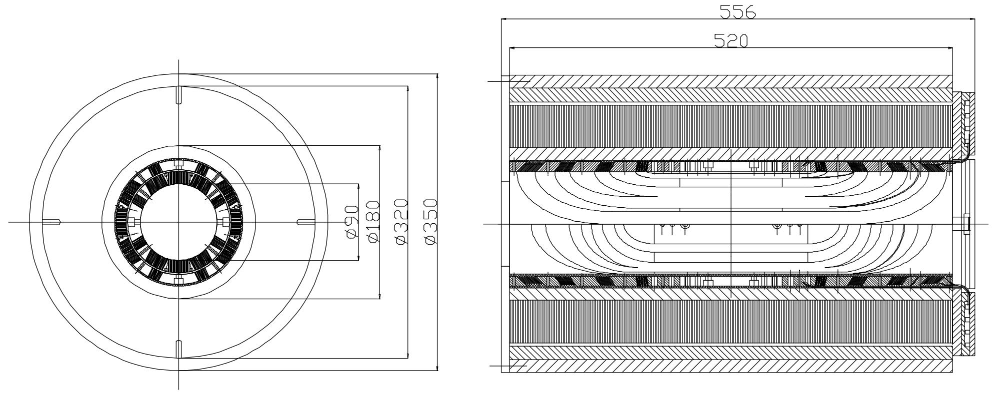

Figure 2: Second MCBX prototype magnet

Figure 1 illustrates the cross-section of the first prototype magnet with an outer diameter of 500 mm. After that a second prototype, whose cross-section is shown in Figure 2, was made using identical coils but with a yoke that was slimmed down by suppressing the holes for the heat exchangers and the busbars. The vacuum impregnated coils containing CNC-machined end spacers are pre-compressed with an aluminium shrinking cylinder. The yoke consists of scissors-laminations to back up the coil rigidity and to centre the coil assembly. Each lamination is designed to support the coils radially in one azimuthal direction only. This is made by off-centring the hole in the lamination by 1 mm with respect to the outer boundary. By sequentially stacking four laminations at angular orientations of 0, 90, 180, 270 degrees respectively the coils can be effectively supported and centred. The laminations move inwards during the cooldown and the blocking keys stop the movement at a pre-defined temperature building-up a circumferential stress in the stainless steel outer shell.

2.2. Magnetics

The nested dipole coils are individually powered and can produce both a horizontal and a vertical field. The nominal field integral is 1 Tm in any direction as shown in Figure 3, which gives a maximum kick angle of 42.8 μrad at 7 TeV. The working point on the load-line for the LHC corrector magnets with vacuum impregnated coils is typically below 60 %. The tolerances for the maximum allowed field errors are very tight in the low-β triplet, where β-functions rise to over 4000 m to achieve the maximum luminosity at full energy.

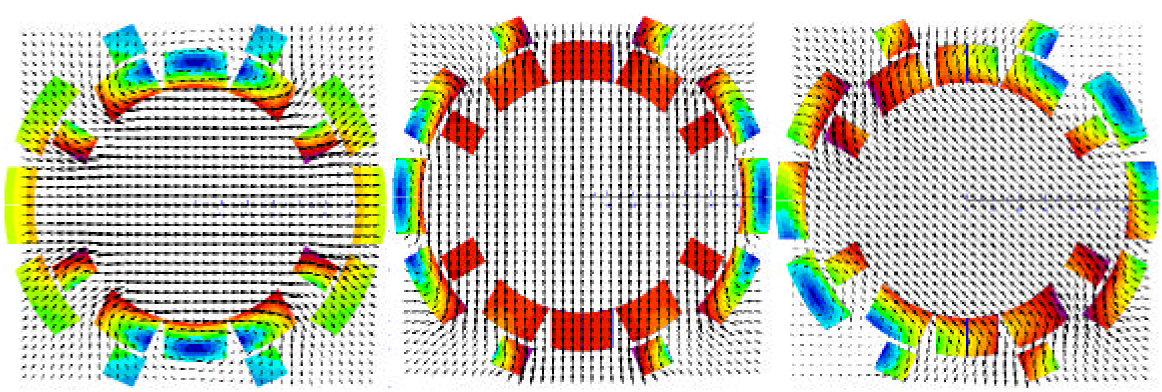

Figure 3: MCBX, different field combinations

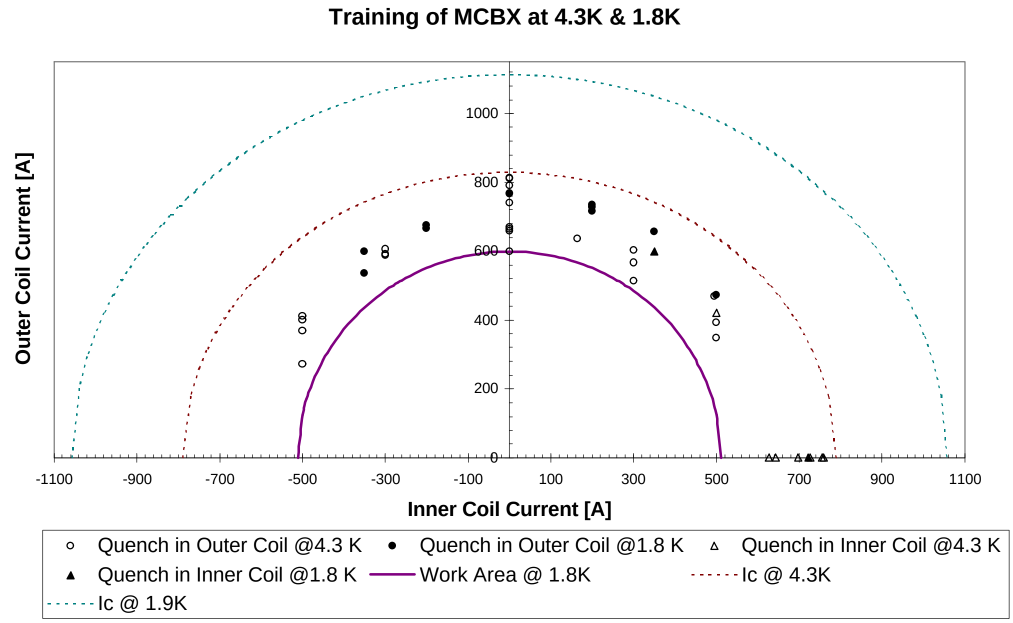

Figure 4: Training of the first MCBX prototype magnet

2.3. Test Results

The first MCBX prototype has undergone the first test campaign including training quenches, static magnetic measurements at warm and at cold, and ramped measurements to study the persistent current effects in the nested coils. After 5 and 6 quenches the vertical and horizontal dipoles were respectively trained to their estimated short-sample current in liquid helium (4.3 K).

Figure 4 presents the training history for different field combinations during the first thermal cycle. The horizontal and vertical axes give the current in the inner and outer coils, respectively. The innermost ellipse shows the working area of the magnet i.e. the 1 Tm field in any direction. The magnet showed always some training with different field combinations as the position of the peak field changes and also the electro-magnetic forces act in different directions. It should be noted that to limit the stress in the coils the maximum current was kept below 800 A. We hope in a next test to go beyond this level and explore the ultimate limits of this magnet. There was also only a minor improvement in the performance when the magnet was cooled to1.9 K.

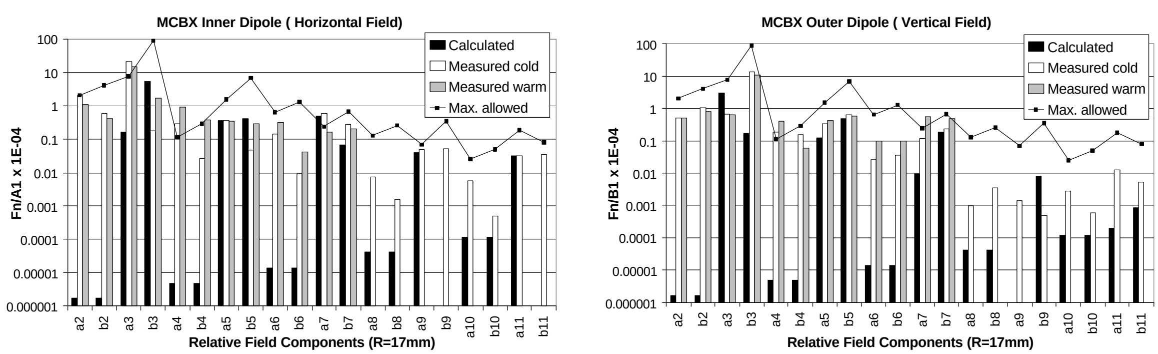

Figure 5: Measured and calculated multipole content of the inner and outer coils in comparison with the maximum allowed field errors

Both static and ramped magnetic measurements were carried out. Figure 5 compares the measured relative multipoles from the inner and outer coils at warm and at cold to the calculated values. There was also a good agreement between the measured and calculated field errors arising from the persistent currents.

3. Skew Quadrupole MQSX

The MQSX skew quadrupole has not yet been made as a prototype. The mechanical design will be similar to the MCBX comprising vacuum impregnated coils, scissors-laminations, and a shrinking cylinder. The preliminary parameter list for two different design alternatives is given in Table II. The coils of the 500 A design are counter-wound in the same way as the LHC spoolpiece correctors and the low-current version is wound with a flat cable of 10 wires. The disadvantage of the latter case is that in total 39 electrical connections have to be made on the end plate.

*Table II: Preliminary design parameters of low-**b** Skew Quadrupole MCQSX*

	Low-current version	High-current version	
MAGNETICS			
Nominal strength	22	22	T/m
Magnetic length	0.4	0.4	m
Peak field in coil	1.5	1.5	T
GEOMETRY			
Overall length	0.6	0.6	m
Coil length	0.5	0.5	m
Coil inner diameter	90	90	mm
Coil outer diameter	104.6	95	mm
Yoke inner diameter	128.6	119	mm
Yoke outer diameter	330	330	
Overall outer diameter	350	350	mm
ELECTRICS			
Nominal Current	0-55	0-500	A
Number of turns/coil	536	53	
Stored energy/magnet	0.9	0.6	kJ
Self inductance/magnet	596	5	mH
CONDUCTOR			
Cross section	0.28	0.913	mm^2
Cross section(metal)	0.21	0.689	mm^2
Copper/NbTi ratio	3.58	1.7	
Filament diameter	7	7	µm
Twist pitch	14	14	mm
Current density (NbTi)	1175	1926	A/mm^2
Margin to quench	76	62.5	%

4. Correction windings

4.1. Magnetics

Each inner triplet contains three corrector packages. The MCBX-magnets will accommodate two nested windings combining layers for either b_6-b_3 or b_5-b_4 corrections and the ones for the a_3-a_4-a_6 corrections will be located in the MQSX. The windings in the MCBX are subjected to a background field of 3 T, which sets a high demand for alignment tolerances due to the associated unbalanced forces. The background field in the MQSX is 1.5 T, however for coil construction and cooling reasons it is considered that it should not have more than three nested layers. The length of the layers will be adapted to the magnet in which they are housed.

Figure 6 illustrates how the magnetic forces on the correction windings will be pointing in different directions. To withstand these forces two options are possible. One is to incorporate the windings in the dipole or quadrupole coil assembly and then vacuum impregnate them all together. The other option is to assemble each set of correction windings as an independent insert rigid enough to withstand the magnetic forces. The second modular option has been taken as it allows more flexibility when it comes to the choice of correction windings.

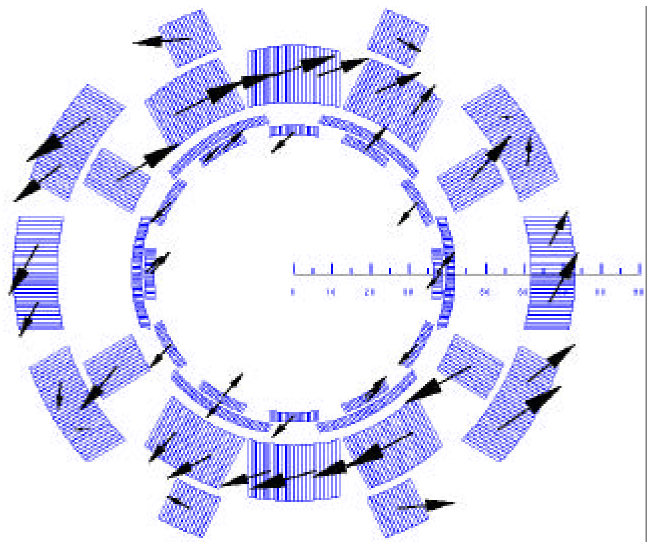

Figure 6: Magnetic forces in the coil blocks of MCBX and b_3-b_6 correction windings

4.2. Design

The cross-section of an insert combining b_3 and b_6 coils is shown in Figure 7. The coils are counter-wound around fiberglass central posts with a 600 A superconducting wire. To reduce the number of connections on the end plate each coil has two radial winding layers. The six dodecapole coils are mounted and aligned with dowel pins on a 1.5 mm thick fiberglass tube. Fiberglass filler pieces are located between the coils prior to wrapping the coil assembly with a pre-preg bandage. Once cured the outer diameter is turned to a precise dimension and the three sextupole coils are assembled in the same way followed by another layer of pre-preg bandage. Finally, an aluminium cylinder is shrunk around the magnet assembly and owing to its higher thermal contraction factor than that of the coils, the radial pressure and therefore the azimuthal pre-compression in the coils increases during the cool down.

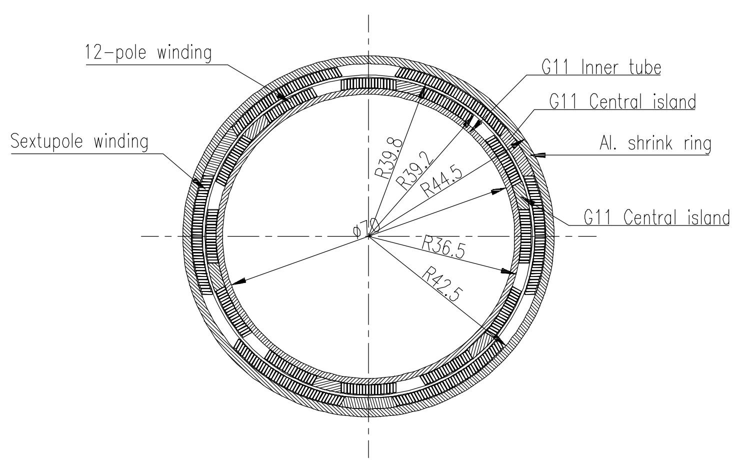

Figure 7: Cross-section of the b_3-b_6 insert

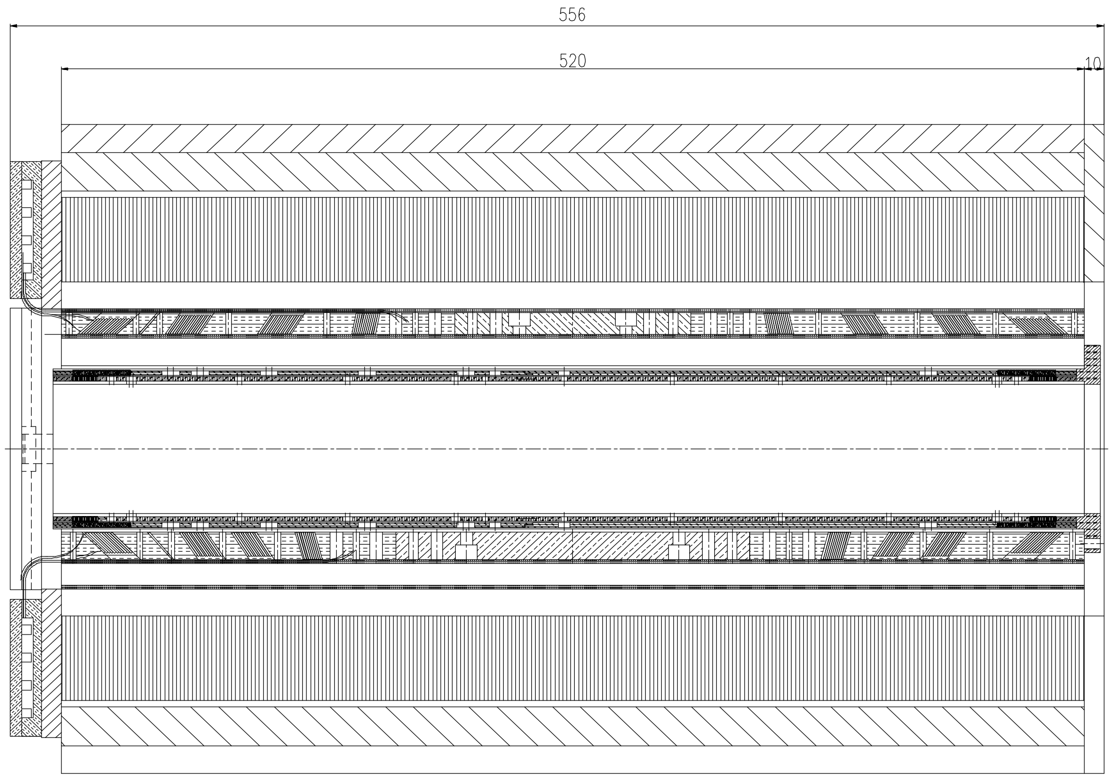

Figure 8: MCBX-b_3-b_6 assembly

The inter-coil connections are done on an end plate, which also includes the dowel pin holes to align the corrector insert with respect to the magnet in which it is housed (see Figure 8). The centering in the non-connection end of the insert is done by means of a precisely machined disk dowelled to the connection end of the MCBX.

4.3. Limitations

Besides the space limitations the choice of the operating current sets certain limits for the design. It is in principle desirable to make the correction windings using a wire that is as thin as possible in order to run at low currents. However, it is important that the inductance does not increase to point where the voltage developed during a quench becomes unacceptably high. It appeared that 50 A is a very minimum. For the first b_3-b_6 prototype the counter-winding technique used for spool-piece correctors of the LHC was adapted. If these coils are wound with a flat cable for easy fabrication, in the same way as several of the LHC correction magnets, the serial connections have to be made on the end flange. Therefore, there is an optimum to be found for the operation at the lowest possible current while keeping the number of connections to be made at the end to a practical level. This might turn out to be something like 100 A.

Another limitation is the field that can be generated by a correction winding. The overlapping dipole field limits the current density in the correction windings. Furthermore, when the correction winding is made of several layers, the additional layers are less effective in creating field as they are further away from the center of the magnet. The result of a number of calculations has been summarized in Figure 9. The field that can be generated on the inner rim of the correction coil is given as a function of the strength of the overlapping dipole field and as a function of the correction coil thickness. It is valid for multipoles from order 3 to 10 and allows estimation of the correction strength that can be obtained.

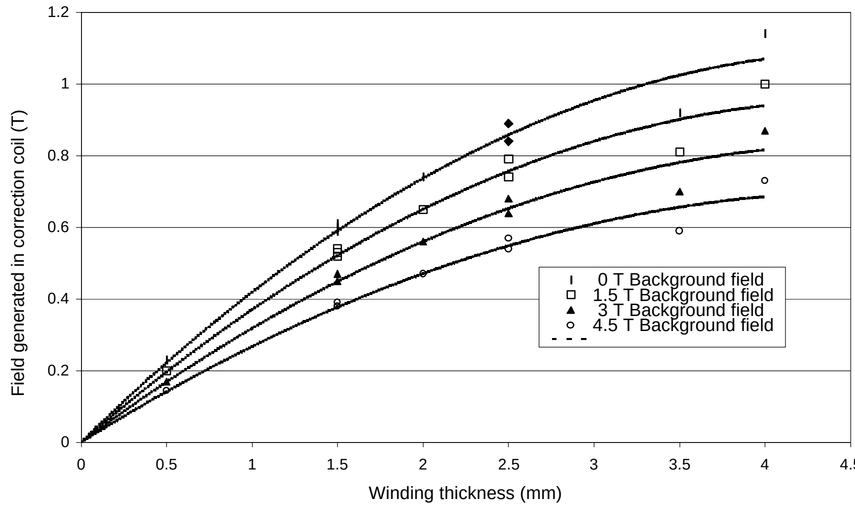

Figure 9: Correction field as function of thickness of correction winding (in overlapping fields of 0 to 4.5 T respectively). Any multipole order from 3 to 10

5. Proposed Correction Packages

In view of the recommendations of this Workshop [6] to consider three correction layers in the C1 and C2 packages (MCBXA and MQSXA in the CERN naming convention) and two correctors in the C3 package (MCBXB), a preliminary design was made to estimate the possible wire sizes and current ratings. He results of this study, Table III and IV, indicate that the required corrector strengths can be reached in all cases with nominal currents close to 120 A, which is one of the LHC corrector powering standards. The only exception are the b6 and a4 correctors which are limited by the criteria of margin-to-quench of at least 40%, and have strengths lower than given in [6]. Further studies are required to define the optimal design for these two correctors which would satisfy all criteria.

Table III: Preliminary parameters of the correction windings in the MCBX

	MCBXB		MCBXA			
	MCTX	MCSX	MCDX	MCDSX	MCOX	
	b_6-corrector	b_3-corrector	b_5-corrector	a_5-corrector	b_4-corrector	
MAGNETICS						
Field at 17 mm radius	0.017	0.029	0.012	0.012	0.027	T
Magnetic length	0.5	0.5	0.5	0.5	0.5	m
Background field	3.3	3.3	3.3	3.3	3.3	T
GEOMETRY						
Overall length	0.6	0.6	0.6	0.6	0.6	m
Coil length	0.55	0.55	0.55	0.55	0.55	m
Coil inner diameter	73	81	73	78	83	mm
Coil outer diameter	366	82.46	75.92	80.92	85.92	mm
ELECTRICS						
Nominal Current	140	100	85	110	125	A
Number of turns/coil	63	34	37	39	52	
CONDUCTOR						
Cross section	0.28	0.28	0.28	0.28	0.28	mm^2
Cross section(metal)	0.21	0.21	0.21	0.21	0.21	mm^2
Copper/NbTi ratio	3.58	3.58	3.58	3.58	3.58	
Margin to quench	41	62	66	56	50	%

Table IV: Preliminary parameters of the correction windings in the MQSX

	MQSX			
	MCTX	MCOSX	MCSSX	
	a_6-corrector	a_4-corrector	a_3-corrector	
MAGNETICS				
Field at 17 mm radius	0.010	0.046	0.068	T
Magnetic length	0.5	0.5	0.5	m
Background field	1.5	1.5	1.5	T
GEOMETRY				
Overall length	0.6	0.6	0.6	m
Coil length	0.55	0.55	0.55	m
Coil inner diameter	73	79	84	mm
Coil outer diameter	75.92	81.92	87.92	mm
ELECTRICS				
Nominal Current	155	180	120	A
Number of turns/coil	31	50	71	
CONDUCTOR				
Cross section	0.28	0.28	0.28	mm^2
Cross section(metal)	0.21	0.21	0.1	mm^2
Copper/NbTi ratio	3.58	3.58	3.58	
Margin to quench	70	40	60	%

6. Planning

The planning of the design and fabrication of the LHC corrector magnets gives priority to the magnets that must be installed in the arcs. Their installation comes earliest and determines the date of commissioning of the machine. The corrector magnets for the insertion regions and inner triplets therefore come slightly later. As Table V shows the deliveries are planned as from September 2001.

Table V: LHC Corrector program

Planspe7.xls	A. lj. 1-6-99						**Work distribution corrector magnets**																																										
										X = required delivery																																							
C = conception	D = design			d = design drawing firm										A = approval						S = spec. approval									O = order					D = delivery						I = installation									
	YEAR/					**1**	**9**	**9**	**9**									**2**	**0**	**0**	**0**									**2**	**0**	**0**	**1**									**2**	**0**	**0**	**2**				
		J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
Supercond.	**Wire**					**S**					**O**						**D**																																
		Some wire is needed earlier for sextupoles -> intermediate order																																															
MAIN DIPOLE																																																	
Spool sextupole	**MCS**	**A**	**S**					**O**					*D*						**X**	**D**																							**I**				
Spool decapole	**MCD**	**D**	**d**	**d**	**d**	**A**	**S**					**O**							**X**					**D**																			**I**				
Spool octupole	**MCO**	**D**	**d**	**d**	**d**	**A**	**S**					**O**							**X**					**D**																			**I**				
		Conclusion 1) Produce Type 2 dipoles first 2) make intermediate sextupoles for first up to 30 MB's in house																																															
MAIN QUADRUPOLE																																																	
Sextupole/Dip.	**MSCB**			**C**	**C**	**C**	**D**	**D**	**A**	**S**						**O**								**X**				**D**																	**I**				
									d	**d**	**d**																																						
Tuning quad.	**MQT/S**						**C**	**C**	**D**	**D**	**A**	**S**				**O**								**X**				**D**																	**I**				
											d	**d**																																					
Lattice Octupole	**MO**								**C**	**C**	**D**	**D**	**A**	**S**					**O**								**X**				**D**														**I**				
													d	**d**																																			
		Problem for fabrication. Installation can start in time but manufacturing capacity not able																																															
		to cope with installation rate (some "holes" could be left)																																															
DISP. SUPPR.																																																	
Long Trim Quad.	**MQTL**						**C**	**C**	**D**	**D**	**A**	**S**				**O**								**X**				**D**																	**I**				
Orbit Corrector	**MCB**										**C**	**C**	**D**	**D**	**D**	**A**	**S**					**O**		**X**										**D**											**I**				
		Must be installed first. Critical for installation																																															
INSERT. QUADS																																																	
Long Orbit Corr.	**MCBL**										**C**	**C**	**D**	**D**	**A**	**S**						**O**												**D**															
RF Orbit Corr.	**MCBR**										**C**	**C**	**D**	**D**	**A**	**S**						**O**												**D**															
Wide Orbit Corr	**MCBY**												**C**	**C**	**D**	**D**	**A**	**S**				**O**												**D**															
Low-b Orbit Corr.	**MCBX**												**C**	**C**	**D**	**D**	**A**	**S**				**O**												**D**															
	(+spools)												**C**	**C**	**D**	**D**	**A**	**S**				**O**												**D**															
Low-b Skew Quad.	**MCQS**												**C**	**C**	**D**	**D**	**A**	**S**				**O**												**D**															

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