The Superconducting Magnets for LHC

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1. Introduction

Already two years ago at the same Conference N. Siegel, presenting the LHC Magnet Team, reported on the super conducting magnets for the LHC [1]. In this contribution we try to briefly recall the main features of the LHC magnet system and to elaborate on the modifications applied to the main magnets resulting from the advancement in the R & D programme for the conductor, magnets and the cryogenic system. We will also give a short overview over the numerous auxiliary magnets. It must be mentioned that the development phase for the magnet system is still under way and further improvements may be implemented before the launching of the series production. This paper should be read in combination with an other contribution where an overview of the present state of the LHC project is given [2].

2. Magnet system overview

The regular lattice has remained, almost, unchanged since the last Protvino meeting. It is referred to in CERN's most recent LHC design report [3], the so-called yellow book. The regular half-cell lay-out with its three twin-aperture dipole magnets of 14.2 m magnetic length and 8.34 T central field, followed by a twin-aperture quadrupole of 3.10 m and a gradient of 223 T/m has been upheld. The dipoles, Fig. 1, will be equipped with sextupole and decapole spool pieces to correct these multipole components created mainly by persistent currents, dynamic ramping effects and saturation.

The quadrupoles will be the principal magnet units of the so-called short straight sections, Fig. 2, which will comprise also two combined sextupole-dipole corrector magnets, dedicated for chromaticity control and orbit corrections and either the octupole corrector magnets or tune quadrupole magnets. The latter ones will equip the units near the ends of each arc. The short straight sections will be the place where the cryogenic supply for each half-cell is accomplished. With respect to the earlier lay-out, a symmetric positioning of the quadrupoles between adjacent dipoles has now been adopted. This became possible by moving the 37 cm long (yoke length) octupole or tuning quadrupole magnets to the connection end of the quadrupoles while keeping the 1.26 m long (yoke length) combined sextupole-dipole correctors on the opposite end. Together with the beam-position monitors, the protection diodes and the cryogenic connection boxes the short straight sections will present the most complex units of the regular arc lattice.

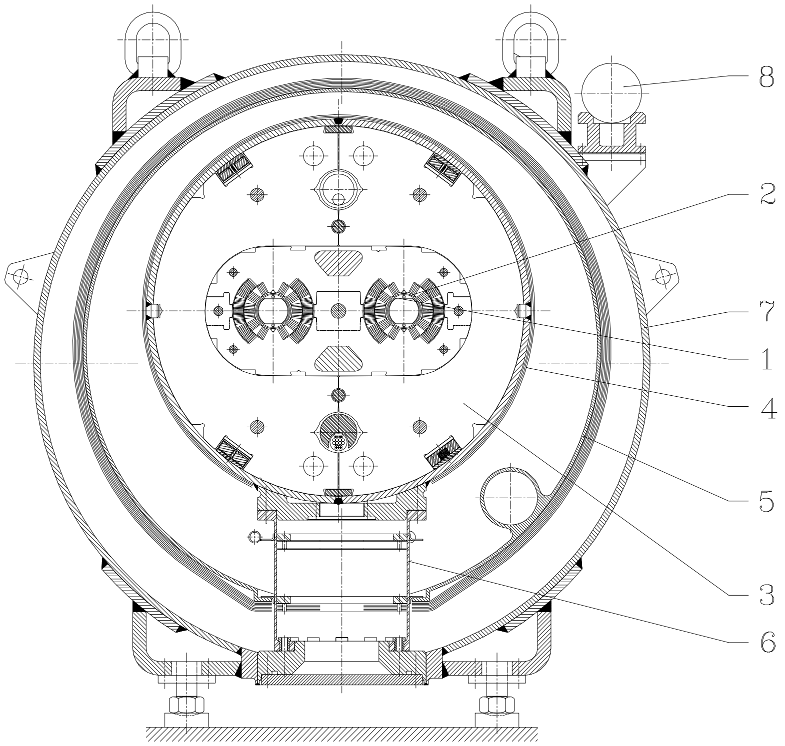
The magnet system will also consist of the dispersion suppressor units which are a combination of regular dipoles and quadrupoles as well as some special trim and skew quadrupoles which will be different in length, completed by a number of dipole, sextupole and decapole correctors.

A further category of magnets are the insertion magnets which will guide the beam not only to the four strong focusing experimental low-b insertions, but also to the two cleaning insertions and the beam dump and RF insertions. Great care has been taken to make maximum use of standard arc magnet designs, but for the cold and warm separation dipole magnets as well as for the large aperture quadrupoles and correctors used in the inner triplets special designs are needed.

3. Modifications during last two years

During the last two years a number of changes in the general lay-out and in some important details have taken place. In mid 1995 it was decided to enlarge the inter-beam distance from 180 mm to 194.00 mm. The latter value is valid at cold operational conditions. This had as a consequence the re-design of all main magnets. This change was motivated by space considerations in the RF sections and by the possibility to enlarge the collars obtaining a better mechanical behaviour during the warm pre-stressing of the coils when applying the collaring operation.

Fig. 1: Cross-section of dipole in cryostat: 1. Cold bore and beam screen, 2. Coil windings, 3. Cold mass at 1.9 K, 4. Radiative insulation, 5. Thermal shield (55 to 75 K), 6. Support post, 7. Vacuum



vessel, 8. Alignment target.

The stress relaxation could be reduced, thus demanding less over-stress before keying the collars together. Further, it makes it possible to use wider cables than the actual 15 mm wide cable for the case where higher performance or more margin to short sample performance should turn out necessary.

The cryostat design up to 1995 consisted in having all cryogenic supply pipes integrated in the cryostat. This made its diameter large and the cryostat and magnet inter-connections a complicated task. For reasons of economy a four feed point scheme was adopted, instead of the earlier current and cryogenic supply from eight points and some of the piping inside the cryostats became prohibitive large. This led to a new study [4], [5] which revealed that a separate cryogenic supply line could overcome these drawbacks. It also helps in making the exchange of magnets more flexible.

4. Magnet research and development programme

The magnet research and development programme has been pursuit along several lines. While initially at CERN the attention was concentrated on involving industrial firms in the development and construction of short dipole models and 10 m long prototype dipoles later, since about three years, an own in-house programme for constructing one metre long models, both single and twin aperture ones, was launched. Since the beginning of this year an assembly facility for up to 18 m long dipoles is in operation at CERN. But further dipole development was entrusted to collaborating laboratories, as the Finnish-Swedish version of a 1 m model [6], the Nb_3Sn high field dipole model Twente University in Holland [7] or the model built in the KEK Laboratory in Japan [8]. All three have produced successful models of versions different from those studied at CERN.

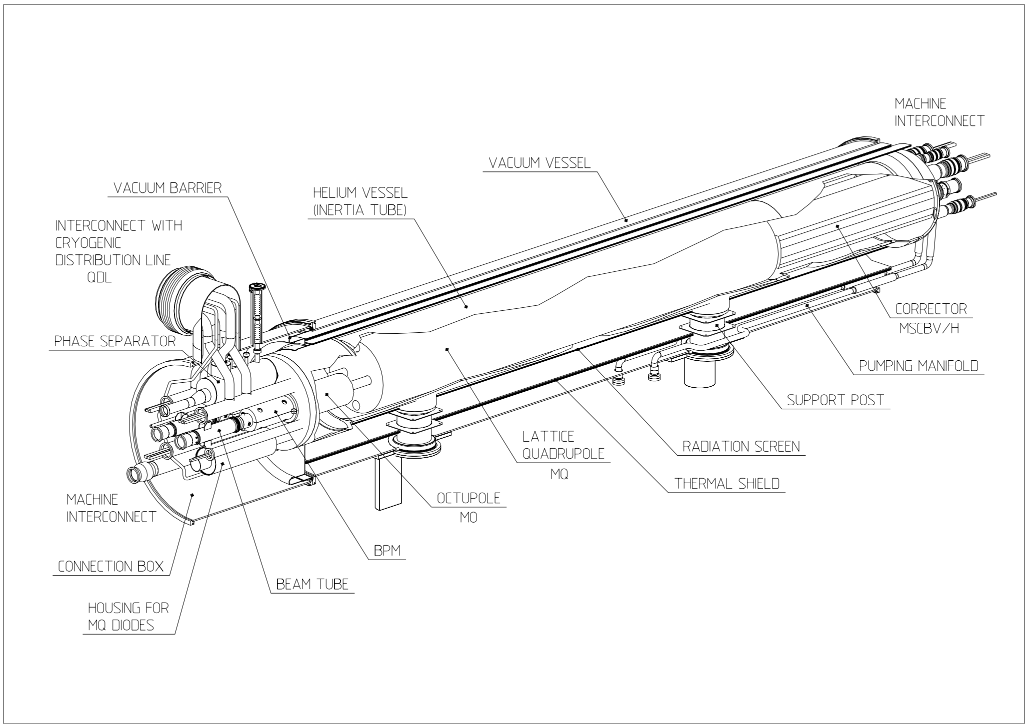


Fig. 2: Short straight section with quadrupole and corrector magnets in cryostat.

The development of the quadrupoles has been from the beginning entrusted to CEA, Saclay in France. Their experience in the development and in the follow up of the fabrication of the HERA quadrupoles qualified them well for this task. As mentioned in [1] this has resulted in the construction of two 3.06 m (magnetic length) real size quadrupoles which have been successfully tested at Saclay and delivered to CERN. In a collaboration protocol, set up in the frame of a special contribution of France to LNS, as

one of the host countries, CEA will ensure the development and tests of two further, slightly modified quadrupole prototypes. CEA will then be responsible for specifying the magnets for the pre-series and series production as well as for the technology transfer and for the follow up of their fabrication in industry.

The development of corrector magnets is advancing through Spanish, English and Danish institutes and firms. Work is going on concerning the development of prototypes of the sextupole correctors (GB), dipole (GB and DK) and quadrupole, sextupole, octupole and decapole correctors (SP).

At CERN a special workshop for fabricating one metre long single and twin aperture dipoles has been set up and can now manufacture this type of magnets in a relatively short time. The ten units built until now have allowed to study different versions of coils as e.g. those having tin coated or uncoated cables, different types of end spacers, different versions of the layer jumps, impregnated or not impregnated coil ends and different cable insulation materials. Sometimes the versions differ also in the assembly method; so-called end cages were used at different degrees of pre-tightening to stop longitudinal coil movements and different temperatures and pressures were applied for reconditioning the coils. Also collaring tests the coils while stretching them were made. Besides these single aperture tests a short twin aperture dipole is presently under preparation and will be tested soon. With this programme of short magnets one wishes to identify all weak points: The tests of these magnets consist in training the magnets in order to evaluate the operational safety margin relative to the short sample limit along the load line and in magnetic field measurements. With the help of quench antennas it could be shown that the weak points where quenches occur usually are in the coil ends and in the layer jump regions.

In parallel to the short model programme the test and magnetic measuring programme for the seven 10 metre long magnets fabricated in four different European firms or consortia has continued. The result of these magnets both in terms of quench behaviour and in their magnetic field quality confirms the choices for the construction of the magnets. Three of them together with one of the quadrupoles mentioned before, form since about two years, the LHC test string which serves to verify all assumptions and precautions for the cryogenic operation, the powering conditions as well as the quench protection measures. Actually this string is running a reliability test campaign where already more than 1500 current cycles have been performed without damaging the magnets, presenting almost 10 years of machine operation. In testing the quench protection system more than 100 quenches have been provoked in different magnets of the string.

5. Dipoles

On top of the modifications mentioned in chapter 3 the parameters of the dipoles have evolved in a few details. While their main options of using combined aluminium alloy collars with iron inserts punched into them has been maintained some improvements will be applied to the cable. Compared to the earlier 15 mm cable the compaction was found to be too high causing too sharp cable edges and thus risking insulation damage. A reduced compaction was also found to allow better liquid helium penetration and thus increasing the minimum energy needed to provoke a quench. Better coolant penetration is also achieved by a modified insulation system which now consists of an all polyimide insulation without the impregnated epoxy glass fibre layer applied in earlier prototypes.

Of great concern for the operation of the machine is the quality of the field inside the magnets. Contrary to classical iron yoke dominated magnets the quality of the field is determined by the positioning of the conductor blocks which form the coil and are around the cold bore and thus the useful aperture. It is more difficult to control the precision of the coil geometry compared to the pole shape of an iron magnet: The pre-stressing of the coils at warm conditions, the coil contraction during cool-down and the enormous electromagnetic forces during operation make it difficult to determine the exact shape of the coils. The problem is complicated by the appearance of persistent currents in the filaments and their influence on the field quality [9],[10]. These persistent currents appear at low excitation and die away once the magnet is ramped up. But it is at these low field levels, especially at injection where the beam is most sensitive to field perturbations. The magnet operation will not be made easier by effects coming from boundary induced coupling currents and their dependence on the inter-strand resistance [11]. These effects show not only a variation of multipoles with longitudinal location, correlated to the strand twist pitch. They also show a time dependency, typically consisting of an initial fast change and then a decay with a time constant of 300 to 400 seconds. The so-called snap-back effect which has been observed on CERN's dipole magnets and which depends on the magnet pre-operation cycling, will have to be accounted for the way the magnets will be ramped up during acceleration [12]. The nominal parameters for the dipole magnets are presently as shown in table 1 [13].

Operational Field	8.36	T
Coil aperture	56	mm
Magnetic length	14.2	m
Operating Current	11'500	A
Operating temperature	1.9	K
Coil turns per aperture, inner/outer	30/52	
Distance between aperture axes (cold)	194.0	mm
Outer diameter of cold mass	570	mm
Overall cold mass length	15.14	m
Outer diameter of cryostat	914	mm
Self-inductance, both channel together	119	mH
Stored energy, both channels together	7.4	MJ
Weight of cold mass	31	t

Table 1: Main dipole parameters.

The mechanical structure for taking the electro-magnetic forces relies on the already early adopted scheme of using combined aluminium alloy collars which contain the coils of both apertures. Since the collars are not strong enough to take the forces these forces are transmitted from the collars via the two vertically split laminated yoke halves to the outer stainless steel cylinder. Into the collars are stamped the so-called inserts, soft iron pieces which serve to minimise the appearance of unwanted magnetic multipole components. It is the subject of delicate magnetic field computations to optimise their shape and to find the right yoke size. In table 2 we give the typically expected multipole components for injection conditions and for nominal excitations. These are the mean values given in units of 10^{-4} relative field errors at 10 mm radius. Note that n = 2, 3 etc. indicate the quadrupole, sextupole and so on components. In the actual beam simulation computations a certain spread has to be taken into account as well as an uncertainty for the mean values which may come from different tolerances in the tooling of different manufacturers.

The computational work to determine of the best distribution of the multipole content is still going on and performed in close collaboration with the beam optics studies. On one hand it is important not to neglect any source which may be creating field perturbations on the other hand only beam simulation tells at which operation conditions some multipoles may be of particular influence. As an example we can mention the eccentric placement of the magnet into their cryostat which by itself will produce a considerable skew dipole component. The dipole is also very sensitive on up-down asymmetries which will produce skew quadrupole components.

n	at injection	at nominal operation	
1 (main field)	0.54	8.4	Tesla
2	-0.25	2.0	B_n/B_1, 10^{-4} units
3	-4.0	0.71	

4	-0.11	-0.13
5	0.015	-0.008
6	0.0018	0.00055
7	-0.0027	0.033
9	0.0028	-0.0101
11	0.0089	0.0075

Table 2: Typical multipole field errors at 10 mm radius, computed for the dipole magnets.

6. Quadrupoles

While the quadrupoles feature the twin aperture configuration the remaining of their mechanical structure is considerably different from that of the dipole magnets. This is governed by the lower electromagnetic forces inherent to the quadrupole magnets. The forces are taken by the collars only, which are stamped out of stainless steel laminations. They must have the lowest possible permeability and the highest possible thermal contraction coefficient. The individually collared coils for each aperture are keyed together and then fixed into the one piece iron yoke laminations, again by key bars. Vertically compressing the yoke laminations, which have flat cut-outs alternatively on their top and bottom, allows to take away any play in the key connection between yoke and collars. The yoke holds together longitudinally with the help of end plates and tie rods. It is stiffened and aligned in a stainless steel inertia tube which provides the support of the assembly and serves as the mechanical reference element. For this the tube has a precisely machined range of fixation thread holes which hold key-bars that centre the yoke via grooves which are punched in the laminations. The inertia tube will also support the other auxiliary magnets of the short straight sections and form at the same time its liquid helium vessel.

Nominal gradient	223	T/m
Coil aperture	56	mm
Magnetic length	3.10	m
Operating current	12’120	A
Coil turns per aperture (inner+outer layer)	4x(10+13)=92	
Inner yoke diameter	180.0	mm
Outer yoke diameter	452	mm
Self inductance for one channel	5.21	mH
Stored energy in one channel	383	kJ

Table 3: Main quadrupole parameters.

For the coil fabrication it is intended to use the same cable as in the outer layer of the dipole magnets. Since the unit length of a quadrupole coil is much shorter than that of a dipole coil layer one profits from the use of the remaining stretches in cable production. This should help to reduce waste in cable fabrication and thus keep costs down. The main quadrupole parameters are given in table 3.

7. Choice of conductor for the main magnets

Already from the beginning it was clear that by means of current density grading the efficiency of the conductor use could be improved [14]. The grading consists in having different conductor cross-sections and thus different current densities in the two layers to increase the current density in the layer where the peak field is lower. By properly selecting the cable cross-sections one aims at achieving the best balance of operational margin to the short sample limits along the load lines of each layer. This must be combined with constraints for a good quality field and by keeping the peak voltages and temperatures in the case of a quench to save values.

A number of different conductor configurations have been tried out. The first prototype magnets, both of 1 and 10 metre length, have been fabricated by 17.0 mm wide cables. While the 17.0 mm wide cable magnets have shown in general a good performance the cable was considered difficult to wind. In an urge to keep the costs down and to increase the efficiency in the superconductor usage, we even tried in one single aperture model the use of a 12.5 mm cable, the same as used for the SSC dipoles. Now we have settled for a 15.1 mm wide cable. This appears to be a good compromise between an efficient conductor use, save quench behaviour and economic fabrication of the cable and coils. The parameters of both cables for the inner dipole layer and the outer one, which is also the one used in the quadrupoles, are shown in table 4.

	Inner dipole layer	Outer dipole layer & Quadrupole	
Strand			
Diameter	1.065	0.825	mm
Cu/Sc ratio	1.6	1.9	
Filament diameter	7	6	mm
Filament twist pitch	25	25	mm
Critical current at 1.9 K	≥ 515 A at 10 T	≥380 A at 9 T	
Cable			
Number of strands	28	36	
Cable width	15.1	15.1	mm
Cable thickness (thin/thick edge)	1.736/2.064	1.362/1.598	mm
Strand transposition pitch	110	100	mm
Critical current at 1.9 K	≥13750 A at 10 T	≥12950 A at 9 T	

Table 4: Strand and cable parameters for main dipole and quadrupole magnets.

The cables are insulated by two layers of 25 m thick polyimid tape, both wrapped with 48 % overlap. A third polyimide tape of 70 m thickness containing 10 m of adhesive is wrapped around this by keeping 2 mm spacing. Under cold condition and compression the nominal thickness of the insulation becomes 120 to 130 m for the broad faces of the conductor and provide enough penetration capacity for the superfluid helium.

8. Auxiliary magnets

Each dipole magnet will be equipped by two pairs of corrector magnets. On one end will sit a pair of sextupole corrector magnets [15],[16] on the opposite (connection) end two decapole magnets will be mounted. These "spool piece" type of magnets will operate well below their short sample limits and their coils must be fabricated in an automatic winding procedure in order to keep costs low. Their function is to correct the main systematic multipole field errors which will be present at different stages of the operation. While at beam injection, at low excitation, the multipoles due to persistent currents will prevail at nominal high excitation, some, mainly sextupole, errors due to yoke saturation will have to be corrected. For each beam all sextupoles and all decapole respectively per beam are envisaged to be powered in series. A powering in four families per beam and type is under consideration.

In the cryostats of the short straight sections will be placed the combined sextupole-dipole magnets on the quadrupole end opposite to its connections. The function of the sextupole is the chromaticity correction while the dipoles will be used for the horizontal and vertical orbit correction. The sextupoles will be powered in two families (D and F) per beam while the dipoles will be powered individually. This is the reason why the corrector dipole currents are limited to not more than 50 A, keeping the thermal losses for their current leads the lowest possible. It is intended to make use of high T_c superconducting current leads for this purpose.

9. Tolerances

One of the concerns in the development of the lattice magnets is the sensitivity of the field quality to the different sources of field errors. Beside those coming from well known effects as the persistent currents and yoke saturation a number of other causes for field imperfections exist. One is the precision with which the coils can be fabricated and assembled. A few hundreds of millimetre in coil block displacements are sufficient to produce undesired multipoles, both normal and skew ones which may have serious repercussions on the stability of the circulating beams. Sophisticated magnetic and mechanical calculations are needed to determine all fabrication dimensions such that at operational conditions the field quality is sufficiently good for the beams. Because it is impossible to verify the geometry at cold conditions, only the magnetic measurements inside the cold bore of the magnet can confirm the purity of field over the aperture region where the beam circulates.

Besides the tolerances of the coils, the vacuum system with its beam screen and the cooling channels attached to it can perturb the field because of the magnetic properties of the stainless steel. Selecting a steel with the lowest possible permeability is thus of utmost importance.

Although most of the magnetic flux passing outside the coil apertures is taken by the iron yoke, the eccentric placement of the magnets inside the cryostat produces skew multipoles, in the case of the twin aperture dipoles mainly a skew dipole component. The eventual presence of a gap between dipole yoke halves has also a certain effect on the dipole field.

10. Outlook on series fabrication

The results with the long and short models as well as the performance of the test string has encourage us to converge to a final design, both for the dipoles and the quadrupoles. The drawings for this and detailed technical specifications for components, like conductor and yoke steel have been drawn up or are under preparation. Market surveys for a number of materials and components as well as for the supply of the dipole cold masses have already been carried out in order to have list of qualified firms to whom the final calls for tenders will be sent.

The mass production of the dipoles will be preceded by a number of pre-series magnets, at least 10 per manufacturer. Their delivery should start by 1999. After their thorough testing at the test stations at CERN it is expected to give the go-ahead for the full series production by the year 2001. The manufacturing of all magnets should last about four years during which a rigorous quality assurance programme will be respected. This will also include warm magnetic field measurements of the coil collar assemblies which should allow to eliminate units being outside the required tolerances. A certain fraction of the dipole magnets, the number of which can only be determined after the experience of the series start up, will be tested and magnetically measured in cold conditions at CERN. The installation of magnets together with all other components and the commissioning of LHC is scheduled to be completed by the end of the year 2005.

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