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G.A. Kirby, R. Ostojic, T.M. Taylor and G. Trinquart*

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Abstract—**The LHC dump insertion features a pair of superconducting quadrupoles located on either side of a 340 m long straight section. Two horizontally deflecting kickers, located in between the quadrupole pairs, and a septum in the centre of the insertion, vertically deflect the two counter-rotating beams past the quadrupoles on the downstream sides, and into the dump areas. Due to the layout, the optical β function in the quadrupoles is around 640 m, the largest around the LHC at injection. The quadrupoles must therefore have enlarged aperture and specially designed cryostats to allow for the safe passage of both the circulating and ejected beams. In this paper we present the design of the twin aperture dump quadrupole based on the 70 mm four layer coil proposed for the LHC low-β quadrupoles. In preparation for model construction, we report on improvements of the coil design and a study of the retaining structures.**

I. INTRODUCTION

The layout of the Large Hadron Collider [1] comprises eight straight sections available for experimental insertions and utilities. One of the straight sections (IP6) houses the beam dump system whose purpose is to remove the beam safely from the collider at the end of a physics run, when the luminosity has degraded and a refill is necessary. It will also be used frequently during setting-up and machine studies and must always be ready in case of equipment malfunction or abnormal beam behaviour which might lead to beam loss and quenching of superconducting magnets. The principle of the beam dump is to kick horizontally the circulating beam into a Lambertson type septum, which bends vertically the extracted beams, so that they can be transported to an external zone sufficiently far away to allow beam dilution, safe installation and shielding. Each ring of the LHC has its own beam dumping system which are both installed in IP6.

The insertion consists of a straight section of about 400 m, with two horizontally deflecting kicker magnets at each end. A vertically deflecting iron septum with a double aperture is installed in the centre of the section. A suitable optics of the dump insertion is achieved with two pairs of quadrupoles, Q3 and Q4, which are located on either side of the kickers. The position of Q3, which sits on the downstream side of the kicker, results from a compromise between the kicker efficiency and the strength of the septum, taking into account realistic values for the aperture of Q3 and the dimensions of its cryostat. These constraints result in a very long drift ($\sim$ 340 m) between the upstream and downstream Q3, and a somewhat unfavourable optics, with a β of 640 m in Q3 and Q4, the largest around the LHC at injection. It is therefore envisaged that these two quadrupoles will be specially built units with a larger coil aperture than in the LHC arcs (56 mm). As the warm kicker is located in between Q3 and Q4, the length of the basic magnet (MQY) was chosen to be 3.25 m, so that both Q3 (one MQY unit), and Q4 (two MQY units) can be operated at 4.2 K. Their cryostats need to be adapted for a different cooling scheme than in the LHC arcs, and in the case of Q3, must allow for the passage of the extracted beam.

In this report we present the design of the 70 mm twin aperture quadrupole for the LHC dump insertion based on the coil design that has been proposed for the LHC low-β insertions [2]. The 1 m model of this quadrupole has been recently successfully tested [3], surpassing in a few training quenches its operating gradient in the LHC high luminosity insertions (225 T/m at 1.9 K) as well as the operating current of the MQY quadrupole (160 T/m at 4.2 K). It is planned to build another two single aperture models, whose coils would also serve for a twin aperture model of the MQY magnet.

II. MAGNETIC DESIGN

A. Coil

The coil of the MQY quadrupole is based on the graded shell concept [4]. A four layer coil with an aperture of 70 mm is wound using two NbTi cables, graded in current density by a factor of 1.5. The low current density cable (Cable 1) is used in the first layer and part of the second layer, forming a low current density shell around the high current density sections of the coil, wound with Cable 2. As shown in Fig. 1, the transition between the

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cables occurs in the middle of the second layer, within the only compensating wedge. As a result, the average current density is maximised, giving a short sample gradient of 270 T/m at 1.9 K. In this topology, the systematic errors are eliminated both by the choice of the pole angles of the coil, and by the current density grading.

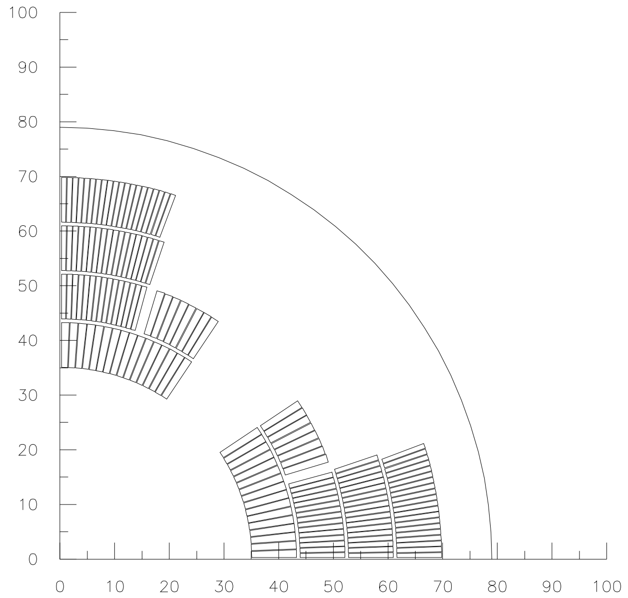

Fig. 1. Cross section of one pole of the MQY quadrupole. The iron laminations are at 79 mm radius

The coil design of the MQY quadrupole is identical to the single aperture model of the LHC low-β quadrupole. This magnet was recently successfully tested [3], and its behaviour during quench was studied in detail. It was determined that in spite of its high inductance (23 mH/m) the magnet safely absorbs its own energy. For quenches at 4.2 K, the peak temperature in the magnet was measured to be 250 K and occurs close to 3500 A, which corresponds to the operating current of the MQY quadrupole of 160 T/m. For this current ($\sim 75\%$ of the estimated conductor limit), the maximum quench velocity of 65 m/s was measured, a factor of three smaller than predicted by adiabatic theory. On the basis of these results, the presently envisaged system of quench protection of the full length (3.25 m) twin aperture magnet, based on firing strip heaters which cover the outer layer of the coil, limits the hot spot temperature to below 400 K [5]. However, for even better quench performance, it has been decided that the cables for the next models will have a modified copper to superconductor ratio. The MQY model quadrupole therefore features cables of identical outer dimensions as the already built single aperture model but with modified strand parameters, as given in Table I. It should be noted that the short sample gradient of the quadrupole is unchanged (205 T/m at 4.2 K) due to the fact that the short sample field is reached in Cable 2 (layer 3), as opposed to previous design when it occurred in Cable 1 (layer 2).

TABLE I
PARAMETERS OF THE CABLES FOR THE MQY QUADRUPOLE (DIMENSIONS IN mm)

Parameter	Cable 1	Cable 2
Width	8.2	8.2
Minor edge	1.13	0.77
Major edge	1.44	0.92
Keystone angle (deg)	2.16	1.05
No of strands	22	34
Strand dia.	0.735	0.480
Packing factor	0.91	0.90
Cu/SC Ratio	1.2	1.7
Filament dia. (μm)	9	10
j_c (A/mm^2) at 4.2 K and 5 T	3100	3000

B. Yoke Design

The conceptual design of the yoke of a 70 mm aperture two-in-one quadrupole was presented in [4]. The basis for the study was the LHC twin aperture lattice quadrupole which is built around a stainless steel collar system that is capable of supporting the magnetic forces without prestressing the yoke [6]. The symmetric yoke laminations are punched as single pieces and assembled around the collared coils. Because of the larger aperture of the coil, it was concluded that the yoke diameter for a 70 mm aperture two-in-one quadrupole had to be increased from the nominal 444 mm to 500 mm to reduce cross-talk and saturation effects. Further development of the 70 mm aperture coil system was focused on the collar-spacer design [2], which simplified considerably the tooling and assembly of the single aperture model. With the cables and coil cross-section optimised for this configuration, a two-in-one yoke needs to be designed which fulfils the structural requirements as well.

The beam separation between the two LHC rings is 194 mm in the present version [1], while the conceptual design of the MQY magnet [4] was based on the separation of 180 mm. This change has considerable influence on the design of the MQY quadrupole as it now becomes possible to consider a yoke design which follows closely that of the lattice quadrupole. In this case, well developed assembly procedures and existing tooling could be reused for a small series of MQY quadrupoles.

The cross sections of the two yoke designs for the MQY quadrupole are shown in Fig. 2 and 3. In the nominal case (collar-spacer), we consider a yoke with two 160 mm diameter openings for placing the collared coils. The yoke has a horizontal split, and transmits the preload forces from an outer force ring to the collars. As in the single

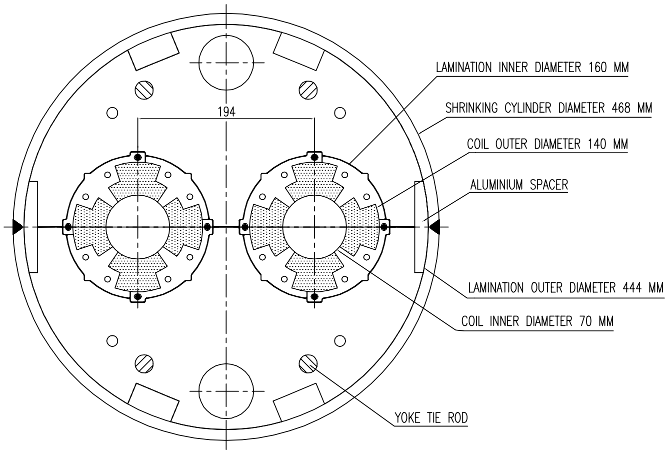

Fig. 2. Cross section of the MQY quadrupole with spacer type collars

aperture magnet, the lamination gaps are closed at cold, forming a very stiff structure which does not allow coil displacement under magnetic forces.

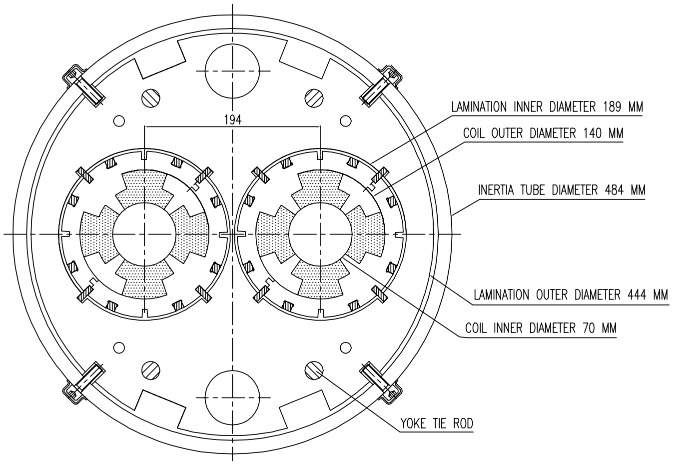

Fig. 3. Cross section of the MQY quadrupole with force supporting collars

In the alternative solution featuring force supporting collars, the two coils are collared separately, and the single piece yoke laminations assembled around the two magnets. The mechanical link between the collars and the yoke is made by four lines of keys at the pole planes which fix and centre the collar assemblies once the laminations are in place and locked with keying rods. The diameter of the two openings in the yoke is 189 mm, leaving a bridge between the two collared coils of 5 mm. The other features of the yoke (opening for the cooling channel, bus bars, locking keys for the inertia tube, etc.) are identical to those of the lattice quadrupole.

Besides the fact that the yoke plays substantially different roles in the structural design, the two proposals differ in the amount of iron and its distribution with respect to the coils. In order to examine this aspect of the yoke design, we have computed the transfer functions and the systematic multipole errors as function of magnet current. The field gradient (B_2) and leading dipole (b_3, b_5) and quadrupole (b_6, b_{10}) type relative multipole errors are given in Table II. It may be noted that the larger diameter of the yoke openings in the design with force supporting collars, while increasing the b_6 error, acts favourably on the dipole type multipoles. In fact, although the two coils are decoupled in the collar-spacer design by more iron volume, the increase of the b_3 multipole with current is more important; b_5 is, however, smaller at the operating current. As expected, differences in iron saturation do not affect quadrupole type multipoles, as seen from the variation of b_6 and b_{10}. In both cases, the beam axis of the two quadrupoles moves inwards by about 20 μm. Except for the b_3 multipole, all field errors are smaller than the LHC lattice quadrupole errors [1]. The increase of the b_3 multipole sets an upper limit for the operating current to about 3700 A. If necessary, it may be reduced below one unit by adjusting the position of the cooling hole, or by repositioning of the yoke tie rods.

TABLE II

Transfer function and systematic multipole errors of the MQY quadrupole in the collar-spacer (A) and force supporting collar (B) versions. The relative multipole errors are expressed in units of 10^{-4} at the reference radius of 10 mm.

Current	Parameter	MQY (A)	MQY (B)
500 A	B_2 (T/m)	24.6	26.3
	b_3	0.026	0.016
	b_5	0.017	0.017
	b_6	-0.092	-0.038
	b_{10}	-0.005	-0.005
2000 A	B_2 (T/m)	98.4	104.8
	b_3	-0.020	-0.238
	b_5	0.017	0.014
	b_6	-0.091	-0.032
	b_{10}	-0.005	-0.005
3000 A	B_2 (T/m)	146.8	153.3
	b_3	-1.300	-2.636
	b_5	0.012	-0.005
	b_6	-0.085	-0.039
	b_{10}	-0.005	-0.005
4000 A	B_2 (T/m)	193.3	199.3
	b_3	-4.70	-5.45
	b_5	-0.005	-0.029
	b_6	-0.087	-0.057
	b_{10}	-0.005	-0.005

III. STRUCTURAL BEHAVIOUR OF THE MAGNET

The behaviour of the two magnet structures under different loading conditions has been analysed with ANSYS and is briefly summarised below.

In the nominal magnet design (collar-spacer), a small quadrupole type press is used for collar assembly. Once locked by rods, the collars compress the coils to about 10 MPa. The collared coils are lowered into the lower half of the magnet, made out of preassembled yoke packs. The centring of the collars within the lamination packs is achieved with triangular locating surfaces in the collars. Following this operation, the upper lamination packs are lowered into place, and centred with the aid of Al-spacers. In the case of the MQY model, the assembly will be compressed with a bolted stainless steel cylinder. As an alternative, the Al-ring and collet technique, which proved very successful in the single aperture version of the magnet, might be used. In the very beginning of the operation, the gap between the collars and the yoke closes and the collar locking rods are released. The collar thereafter acts as a spacer, transferring the compressive forces to the coil. The yoke gap gradually closes from the average initial value of 0.36 mm as the compressive force builds up. In order to maintain identical compression of all poles, the yoke gap is tapered, so that the nose section closes on completion of yoking; at the edge of the yoke legs the gap is 0.16 mm. The average azimuthal stress in the coil at this stage is about 60 MPa.

Due to differential contraction of the structure during cool-down to 2 K, the gap in the outer leg of the yoke closes completely. The azimuthal stress in the coils increases with respect to room temperature conditions, and is on the average 75 MPa.

When the magnet is energised to its nominal current of 3500 A, the average azimuthal stress decreases to about 40 MPa, with the minimum stress greater than 20 MPa. The gaps are closed with a force of about 1000 N/mm, while the magnetic radial force is 450 N/mm. As a consequence, the structure is very rigid with maximum coil deformation of 0.012 mm.

The behaviour of the structure in the version with the force supporting collars is quite different. In this case, the collars exert the prestress during all conditions, and must contain the action of the explosive magnetic forces within minimal bending and displacement. The structural role of the yoke is limited to eliminating torsion and transmitting the centring references to external fiducials. The main difference with respect to the structure already developed for the lattice quadrupole is that the diameters of the coil and of the collar are slightly increased. The collar width itself is almost identical; however, its bending resistance is increased as the pole widens in the region of the outer layers of the MQY coil. Furthermore, the total magnetic force is about 75% of the lattice quadrupole.

An analysis of the structural properties of the force supporting collars confirms the basic conclusions of a similarity study; the bending strength of a 23 mm wide stainless steel collar is sufficient to contain magnetic loading with similar values of residual coil compression and coil displacement as for the collar-spacer structure given above. The coils stress history is however different since substantial force is needed to drive the locking keys in place. Indeed, due to spring-back, the pressure applied during collaring may approach 100 MPa for a residual coil prestress of about 70 MPa. The choice of this solution may therefore imply a revision of the coil insulation system.

IV. CONCLUSIONS

In this report we have presented the design of the 70 mm twin aperture quadrupole for the LHC dump insertion. The design is based on the four layer coil that has been proposed for the LHC low-β insertions, and recently successfully tested in a 1 m model magnet. Another two single aperture models, incorporating slight modifications to the cable parameters and coil insulation, are planned to be built. After testing, these magnets will be disassembled and the coils used in a twin aperture magnet. A design of the retaining structure of the magnet based on the collar-spacer concept has been presented, as well as an alternative approach, based on a force supporting collar system, which follows closely the design and tooling of the LHC lattice quadrupole.

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