A First Baseline for the Magnets in the High Luminosity LHC Insertion Regions

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***Abstract*—The High Luminosity LHC (HL-LHC) project aims at accumulating 3000 fb^{-1} in the years 2023–2035, i.e., ten times more w.r.t. the nominal LHC performance expected for 2010–2021. One key element to reach this challenging performance is a new insertion region to reduce the beam size in the interaction point by approximately a factor two. This requires larger aperture magnets in the region spanning from the interaction point to the matching section quadrupoles. This aperture has been fixed to 150 mm for the inner triplet quadrupoles in 2012. In this paper, we give a first baseline of the interaction region. We discuss the main motivations that lead us to choose the technology, the combination of fields/gradients and lengths, the apertures, the quantity of superconductor, and the operational margin. Key elements are also the constraints given by the energy deposition in terms of heat load and radiation damage; we present the main features related to shielding and heat removal.**

***Index Terms*—Dipoles, low-temperature superconductors, quadrupoles, superconducting accelerator magnets.**

I. INTRODUCTION

THE FIRST proposal for increasing LHC luminosity goes back to the beginning of the century [1], relying on a more intense beam and on a smaller size of the beam at the interaction point. In order to reach this second target, one has to replace the 70-mm-diameter inner triplet with a larger aperture magnet. First proposals focused on a 90-mm-aperture inner triplet quadrupole using the Nb_3Sn technology. This motivated the LHC Accelerator Research Program (LARP) [2], launched in the US during the LHC construction. Successive studies showed that triplet apertures larger than 90 mm can bring additional performance, while shielding the magnets from the collision debris [3], [4].

TABLE I
PARAMETERS OF THE MAIN HL LHC MAGNETS

		Triplet Q1,Q3/Q2a,b	Orbit corrector	Sep. dipole D1	Recom. dipole D2	Large 2-in-1 quad Q4
Aperture	(mm)	150	150	150	105	90
Field	(T)		2.1	5.2	3.5	
Gradient	(T/m)	140				120
Mag. Length	(m)	8.0/6.8	1.2/2.2	6.7	10.0	4.5
Int field	(T m)		2.5/4.5	35	35	
Int gradient	(T)	1120/938				544
Peak field	(T)	12.1	3.9	6.1	4.1	5.9
Current	(kA)	17.5	2.2	11.0	6.8	16.0
j overall	(A/mm^2)	528	455	1695	1040	2458
Loadline margin	(%)	18%	45%	30%	56%	20%
Stored energy	(MJ/m)	1.440	0.090	0.294	0.140	0.204
Saturation	(%)	9.0%	0.0%	9.0%	13.0%	
Material		Nb_3Sn	Nb-Ti	Nb-Ti	Nb-Ti	Nb-Ti
No. layers		2	1+1	1	1	1
Cable width	(mm)	18.1	4.37	15.1	15.1	15.1
Cable thick. in.	(mm)	1.405	0.819	1.362	1.362	1.362
Cable thick. ou.	(mm)	1.595	0.871	1.598	1.598	1.598
Ins. thick rad	(mm)	0.150	0.105	0.130	0.130	0.160
Ins. thick azi	(mm)	0.150	0.105	0.110	0.110	0.145
No. strands		40	18	36	36	36
Strand diam	(mm)	0.85	0.48	0.825	0.825	0.825
Cu/NonCu		1.2	1.75	1.95	1.95	1.95

In November 2011 a design study for the LHC luminosity upgrade has been launched, with the target of delivering a technical design for the Interaction Region (IR) layout by 2015 [5]. After the selection of the triplet aperture in July 2012, we have now taken the main choices for the other magnets of the IR (correctors, separation/recombination dipoles, . . .), such as technology, fields, apertures and lengths (see Table I). Here, we summarize these choices, giving main motivations and possible alternatives.

II. TRIPLET QXF

The triplet is the source of performance: we selected the Nb_3Sn technology giving larger peak field, i.e., larger apertures and/or larger gradients. The 70-mm, 200 T/m of the LHC baseline will be replaced by a 150-mm aperture triplet operating at 140 T/m (see Table I), allowing half the beam size and increased peak luminosity up to a factor four [6], [7]. Thanks to Nb_3Sn, the increase in length is only 30% w.r.t. LHC, i.e.,

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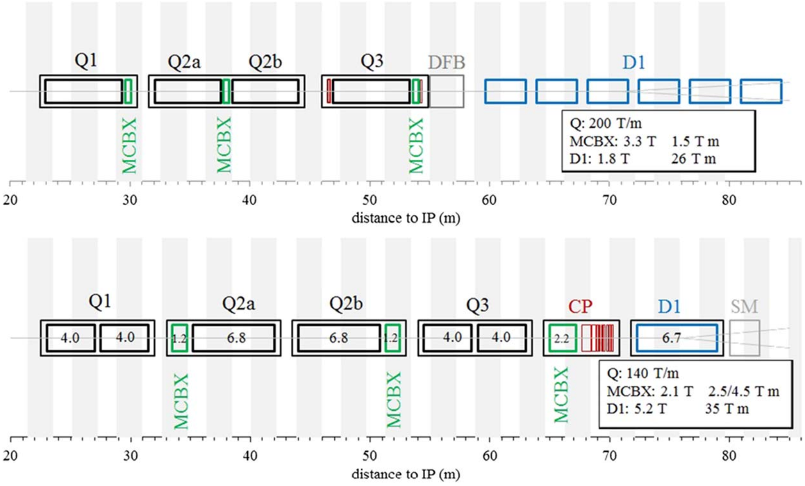

Fig. 1. Layout of the LHC (top) and HL-LHC (bottom) from the first quadrupole to the separation dipole. DFB in the top layout is the cryogenic feedbox hosting the current leads, while SM in the bottom layout is the shuffling module hosting the SC link coming from new DFB located on ground surface.

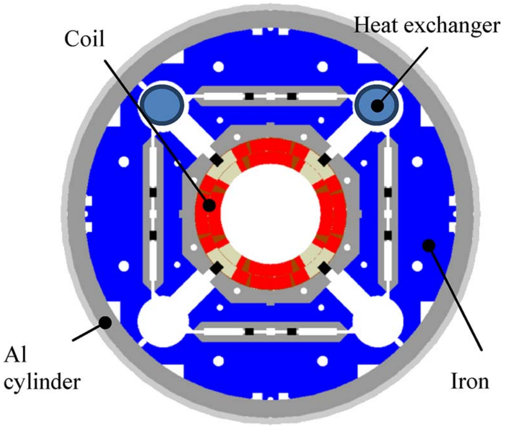

Fig. 2. Cross section of the inner triplet [9].

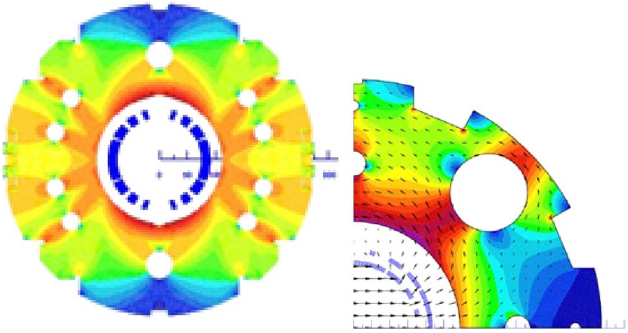

Fig. 3. Cross section of the D1(left) [14] and tentative cross section of the orbit corrector (right) [17].

we go from a 30-m-long to a 40-m-long triplet (see Fig. 1). The design of this magnet relies on 10 years of effort by the LARP collaboration [8]. The inner triplet quadrupole QXF [9] is a scaled-up version of the HQ quadrupole [8], successfully built in two 1-m-long models. In order to maximize the performance, a challenging margin of $\sim$20% on the loadline has also been chosen. The design and the status of the project is presented in [9]. The peak field is 12.1 T.

The structure (see Fig. 2) to manage the stress of 150 MPa due to Lorentz force is given by an aluminum cylinder and loaded with bladders and keys, allowing precise stress control [10]. One of the main challenges of this magnet is the protection [11]–[13]: the time margin available to the protection system to quench the magnet is of the order of 40 ms (it is 100 ms in the LHC dipoles), i.e., just at the limit of present electronics and quench heaters.

III. SEPARATION DIPOLE D1

The longer space needed by the triplet is recovered by replacing the resistive D1 with a superconductive magnet (see Fig. 1). The separation dipole has the same aperture as the triplet, i.e., 150-mm-aperture, with an operational field of 5.2 T and a length of 6.7 m [14]. This magnet, as the triplet, operates in a regime of strong saturation (about 9%, see Table I). Considerable work has been carried out on the iron shape to optimize the field quality at high field. Fearing a large heat load, a margin of 30% on the loadline has been initially taken, and an aperture of 160 mm to allow for thicker shielding. The results of the energy deposition simulations [15] showed that the heat load is not significant with the heavy shielding, allowing reduction of the aperture to 150 mm (see Table I). The mechanical structure is based on a precollaring, with prestress given by the iron and shell welding (see Fig. 3). The assembly prestress needed to keep the coil compressed at nominal current is $\sim$70 MPa. Details on the design are given in [14]. We are also considering the option of reducing the margin to 20%: this would increase the field to 5.9 T, and reduce the length to 6 m, at the price of a higher saturation component. The drawback is a larger stress, which could reach the limits of insulation [14] during the assembly phases.

The option of a Nb_3Sn magnet, considered in the past, [16] has been now discarded, as the gain of a few meters (less than four, with an 11 T dipole) is not considered critical in this location and has no effect on performance. In addition, with such a large aperture the stresses would have been at the limit of the Nb_3Sn damage level.

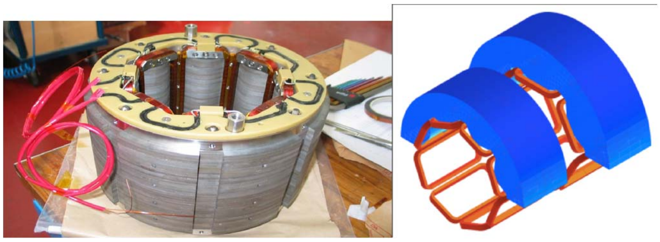

Fig. 4. Superferric correctors.

IV. Orbit Correctors

Horizontal and vertical orbit correctors are needed at each quadrupole. The required bending strength is 2.5 T · m close to Q1 and Q2, and 4.5 T · m close to Q3. Given the large aperture, a cos theta option without nested coils, even with a large field as 4 T, would need 0.5 m of straight part, plus 0.2 m of ends, plus space for connections [17]. Therefore, one would need for the 2 T · m case at least 2 m per corrector (horizontal and vertical), with a non-negligible impact on performance. With a nested option and a moderate field of 2.1 T, we manage to have a 1.2-m-long magnet (see Fig. 1).

The global saving on the whole triplet length given by the nested layout is more than 3 m, equivalent to a 10% increase of the triplet gradient. Preliminary studies have been carried out, with the development of an 18-strand cable of very small width (4.5 mm, see Table I and Fig. 3) [17]. With a one-layer coil, 2.1 T operational field is reached with a very comfortable 45% margin on the loadline (see Table I). The main challenge of this magnet is a mechanical design that manages the torque of 90 kN · m/m when both correctors are at nominal field.

The option of increasing the field to 3 T, thus reducing the margin to 30%, would gain 1–1.5 m at the price of twice the torque.

V. High Order Magnet Correctors

Today, we have nested correctors providing a very compact layout (see Fig. 1, top). In the HL-LHC era, the sensitivity of the beam to high order multipoles in the triplet will be large and for several multipoles there are no beam observables. The requirement is to have nine high order correctors, starting with a skew quadrupole, and going up to order 6. In order to have a transparent operation in this critical region of the accelerator, a non-nested option has been considered, which also avoids crosstalk between different magnets.

We considered the superferric option developed in CIEMAT [18] for the EU program FP7-SLHC. Even though the field is limited by the iron saturation, this option has the appealing advantage of allowing very short ends, as the windings are rectangular racetracks (see Fig. 4).

MgB_2 [19] or Nb-Ti conductors are considered, with the iron at 1.9 K. The short end allows a compact layout even in the case of a non-nested geometry. The whole block of correctors takes a couple of meters, plus the skew quadrupole, which is 0.7 m long. Most of the objects are ~0.1 m long. Prototypes have been already been built (with 140 mm aperture) in the framework of the Phase I upgrade [18].

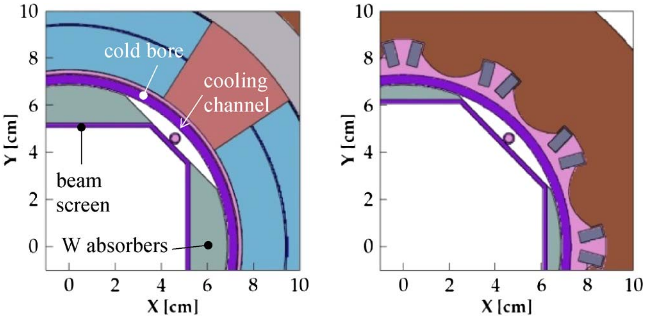

Fig. 5. Cold bore, beam screen, and W shielding in the triplet and correctors.

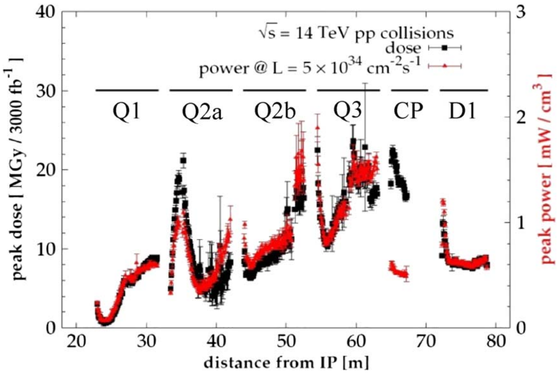

Fig. 6. Peak heat load and peak radiation dose for HL LHC in the coil (peak luminosity of 5×10^{34} cm^{-2} s^{-1} and 3000 fb^{-1} of integrated luminosity).

VI. Heat Load and Radiation Damage From Q1 to D1

The larger peak and integrated luminosities pose issues on the heat load and on the radiation damage, respectively. The solution is to have a large aperture triplet, to make space for thick shielding: results from energy deposition simulations [15], [20], [21] show that the magnets can be protected from the collision debris through appropriate shielding. This is an additional reason (beyond getting to smaller β^*) for requiring larger triplet apertures.

The mechanical requirement is to have a 4-mm-thick stainless steel cold bore to withstand pressure during a quench, plus a 2-mm-thick beam screen, internally coated with Cu to decrease the impedance. In addition, we add a 6 mm thick absorber in the angles where the load is larger, using high-Z, high density material (tungsten). Moreover, 16 mm tungsten absorbers have been considered in the Q1, which has ends exposed to considerable debris radiation and, on the other hand, does not suffer from stringent aperture limitation (see Fig. 5). With this shielding one can operate in HL-LHC at the same levels of LHC, i.e., below 2 mW/cm^3 peak heat load, and 25 MGy of radiation dose (see Fig. 6) despite the five times larger peak luminosity, and the ten times larger accumulated debris from the interaction point.

VII. Cooling

The heat load coming from the collision debris is the dominating factor of the cooling system. In the HL-LHC the particles coming from the interaction point, bent by the magnetic field of the triplet, correctors and separation dipole, deposit about

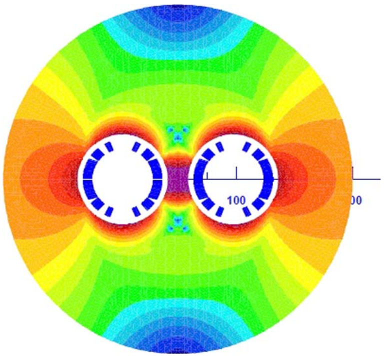

Fig. 7. Tentative cross section of recombination dipole D2.

1300 W on the string from Q1 to D1 shown in Fig. 1. Half of this is intercepted by the beam screen, which has an operational temperature of 5–20 K, and half goes on the so-called cold mass, i.e., the part of the magnet at 1.9 K. The removal of the heat load at 1.9 K is done through two separate systems of heat exchangers, one covering the triplet and the 1.2-m-long orbit correctors, and the second one covering D1 and the corrector package (CP, see Fig. 1 bottom). For the triplet, the 77-mm-diameter heat exchangers are at 45°, respecting the quadrupole symmetry (see Fig. 2). Two out of the four holes are used by heat exchangers. The same holes are present in the 2 m long orbit correctors. On the other hand, the separation dipole and the high order correctors are cooled by one 50 mm diameter heat exchanger, at 90° (see Fig. 3).

The beam screen receives 700 W from the debris, plus another 100 W from the circulating beam (electron cloud, impedance, plus other effects). The cooling needs two tubes of ∼8 mm diameter. The engineering of this component is a critical part of the project.

VIII. RECOMBINATION DIPOLE D2

This magnet is placed at 138–148 m from the IP (see Fig. 2, compared to the 72–78 m position of D1 readable on the horizontal axis), where the D1 kick has separated the beams to the nominal distance. It has to provide 35 T m of integrated field to bring the beams back on parallel paths. The main challenges come from the impact of the two-in-one magnetic structure on field quality [22]. Apertures are increased from the present baseline of 80 mm to 95–105 mm. The nominal field is 3.5 T, with a 10 m length, and a very comfortable 56% margin (see Table I). The larger aperture, the beam separation fixed, has the drawback of creating a magnetic coupling between the two apertures (see Fig. 7), producing very large systematics b_2 (70 units) and b_4 (5 units). Moreover, the saturation produces a large b_3 (50 units) and b_5 (20 units). A careful shaping of the iron, as done in RHIC or in the LHC dipole, is needed to reduce these components. The result of this optimization will determine the final aperture and level of operational field.

One can also consider the option of a larger field of 5 T to get a 7 m long magnet, thus saving 3 m of space, which in this region is more important than, for example, near D1, because of the presence of the new crab cavities [23]. The drawback is a smaller but still comfortable margin, at the expense of larger saturation, possibly making field quality considerably worse.

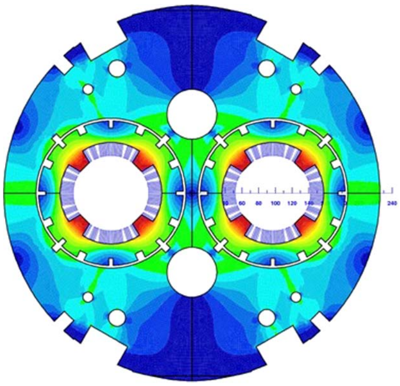

Fig. 8. Cross section of large aperture quadrupole Q4.

IX. TWO-IN-ONE LARGE APERTURE QUADRUPOLE Q4

Q4 is the first quadrupole with beam circulating in separated vacuum chambers and is placed after the recombination dipole D2, at 168 m from the IP. Its aperture is increased from the present value of 70 mm to 90 mm. As for the D2 case, there is a large magnetic coupling between the apertures, because of the larger aperture and the beam separation fixed to 194 mm [24]. For this reason a pretty thin coil of 15 mm width, using one layer of LHC main dipole cable, has been adopted. With a margin of 20% on the loadline one reaches 120 T/m, still providing a short magnet of 4.5 m (see Fig. 8). Larger cable width would leave no space for the iron.

The mechanical structure is based on self-supporting collars. The design team adopted the enhanced insulation [25] tested in the MQXC model [26] as baseline. This allows helium to reach the strands, giving a more efficient heat removal. An alternative design based on two layers of a thinner (7-mm-width) cable has been considered, which lowers operational current from 16 to 5 kA. Indeed, the one layer option requires no quench heaters, and can be done with pieces of LHC main cable production refused for being too short; therefore this design has been adopted.

X. CONCLUSION

The luminosity upgrade project HL LHC started in October 2010. After the selection of the triplet aperture of 150 mm, done in July 2012, in the past year we focused on the definition of the baseline of the LHC interaction region.

In this paper, we present the main choices for the technology, aperture, margin, operational field and gradients, lengths, margins and cables for the magnets from the triplet up to the fourth quadrupole Q4, in the region where the beams are separated and travel in two different apertures. Alternative options are also discussed. We now plan to start the engineering work to be able to test the first short models in 2015–2016 to allow sufficient time for eventual modifications and then proceed to construction to meet the goal of installation in 2022.

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