Development of a Short Model of the Superconducting Separation Dipoles D2 for the High Luminosity Upgrade of LHC

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Abstract—The luminosity upgrade of the Large Hadron Collider requires that the new separation/recombination dipoles D2 deliver a field integral of 35 Tm. A design has been developed of a twin dipole generating a magnetic field as high as 4.5 T in apertures of 105-mm and 7.78-m magnetic length. The magnetic field direction is identical in both apertures causing not negligible magnetic cross talk, which could be highly detrimental for the field quality. In order to minimize the cross talk effects a design based on asymmetric coils has been developed in the past years. Recently, the design has achieved a level of maturity allowing the starting of a second phase of development involving the construction of a short model preliminary to prototyping activities. The short model (1.6-m long) has been designed in all aspects and it is presently under construction in industry. The contribution is focused on the design of the short model with emphasis on the mechanical aspects, which includes a novel approach to the integration of coils in the mechanical structure through the use of Al-alloy sleeves.

Index Terms—Superconducting magnets, dipoles, accelerator magnets.

I. INTRODUCTION

T HE CERN medium term plan includes a substantial upgrade of the Large Hadron Collider [1] to increase the collision luminosity up to an integrated value of 300 fb⁻¹ per year. The new configuration, known as High Luminosity LHC (HL-LHC) [2] is planned to be in operation within 2025.

A relevant contribution to the luminosity upgrade is given by a set of new superconducting magnets placed at the two sides of the interaction regions (IR) of the ATLAS and CMS experiments [3]. Among these magnets an important role is played by the dipoles, D1 and D2, recombining and separating the particle of the two proton beams around the IR [4]. This paper is focused on dipole D2, a twin aperture (105 mm each one) magnet with a separation between apertures of 188 mm, generating in both apertures an integrated magnetic dipolar field of 35 Tm with the same polarity.

Manuscript received August 25, 2017; accepted November 2, 2017. Date of publication November 13, 2017; date of current version November 30, 2017. (*Corresponding author: Pasquale Fabbricatore.*)

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Digital Object Identifier 10.1109/TASC.2017.2772779

In a previous publication [5] the preliminary design of the D2 magnet has been presented. In order to compensate the cross talk of the magnetic field between the two apertures, caused by the identical magnetic field orientation, a magnetic design was developed based on a left/right asymmetric lay-out of the coils. A suitable shaping of the iron yoke with an elliptical cross section to control the saturation effects has been developed as well.

The design of D2 dipole has been further refined for taking into account updated indications coming from the High Luminosity project and integration constraints of D2 into the beam line. Once the design achieved a satisfactory level of maturity, the construction of a short model (1.6 m in length) has been recently launched with the aim to check the feasibility of the technical solutions involved in the proposed design.

In this paper, after discussing the present lay-out of the D2 magnets and the motivations of the technical choices, the design of the short model is presented. Some mechanical aspects of the design are discussed because of the presence of an Al-alloy mechanical containment of the collared coils, constituting a novel approach to the integration for this kind of magnets.

II. THE PRESENT DESIGN OF D2 DIPOLE

Starting from the basic idea that the magnetic cross talk between the two apertures can be suitably compensated through a left/right asymmetric coil design and a proper shaping of the iron yoke, a design of D2 was performed involving single layer coils composed of 5 blocks. The conductor is the same Rutherford cable already used for the outer layer of the bending LHC dipoles. The coil characteristics are shown in Table I. The cross section of the magnet is shown in Fig. 1 and the details of the collared coils in Fig. 2.

The components of the magnet are:

- the two specular apertures with asymmetric coils made of five blocks for a total of 31 turns;
- the collars providing the mechanical pre-stress and the coil containment. To be noted that the poles are not integrated with collars but are separate pieces for allowing the construction of only a collar type rather than two;
- the Al-alloy sleeve containing the collars with the main role to hold the repulsive force of 196 kN/m applied between the two coils at full current;

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Characteristics	Unit	Value
Bore magnetic field	Т	4.50
Magnetic length	m	7.78
Peak field	Т	5.26
Operating current	kA	12.34
Stored energy	MJ	2.28
Overall current density	A/mm ²	443
Magnet physical length	m	8.11
Aperture	mm	105
Beam separation (cold)	mm	188
Operating temperature	K	1.9
Margin on load line	%	33
Multipoles variation due to iron saturation		<10 unit



Fig. 1. Cross section of the two-in-one D2 dipole, including the coils integrated into the collars, Al-alloy sleeve and iron.



Fig. 2 A close detail of the two apertures. The collared coils are mechanically aligned trough two stainless steel keys. The free space between the two collared coils is occupied by the two Φ 33 mm longitudinal tie rods.

- the six stainless steel tie-rods for controlling the longitudinal stress, passing through the holes of the iron yoke and between the two collared coils;
- 5) the iron yoke in two halves coupled in the pole region through steel clamps.

The magnetic field quality has been optimized considering the 3D effects of the coil ends. While the odd harmonics can be



Fig. 3. Geometrical and saturation normal multipoles b_2 and b_3 as function of longitudinal position at nominal field (The coil end without electrical connection is shown).



Fig. 4. Geometrical and saturation integrated normal multipoles from b_2 to b_5 vs the magnetic field in the bore.

suitably managed and geometrical layouts can be found giving integrated values close to zero, the even harmonics in the coil ends, in particular b_2 , cannot be canceled. Starting from a detailed study of the contribution to b_2 of the coil ends (see Fig. 3), the quadrupole contribution in the straight section was set to b_2 = -6 units for obtaining an acceptable integrated value (see Fig. 4). To be noted that the lower multipoles were optimized at a magnetic field slightly lower than 4.5 T

III. THE SHORT MODEL OF D2 DIPOLE

The D2 design achieved a degree of maturity allowing moving to the following step consisting in the construction of a short model, for checking the design choices and verifying the feasibility of the magnetic cross talk compensation through asymmetric coils. This activity is performed in the framework of collaboration between CERN and INFN having as objectives not only the development of a short model but also the construction of a full length prototype within the end of 2019.

The magnetic analysis showed that with an overall coil geometrical length of 1600 mm there is a longitudinal central region of about 400 mm with limited effects due to the coil ends. On this basis a short model magnetic design was developed since first half of 2016 and used as basis of an international tender for construction. The contract to industry was awarded at the end of 2016 and the model has just entered into the construction phase.

For the sake of clarity it should be mentioned that since the beginning of the industrial contract the short model design was completely frozen, meanwhile the design of D2 magnet



Fig. 5. Longitudinal cross section of the short model. One can see that the external iron yoke is not covering the coil ends for limiting the peak field in these regions. The magnetic steel is here replaced by stainless steel.



Fig. 6. The connection side of the short model with cable routing, three electrical joints (enclosed in G11 bolted boxes), the large plate in gray for axial pre-stress (partially hidden by the green plate supporting the conductor joints and the connectors for instrumentation).

is still progressing and including modifications coming from updated analyses, external constraints (integration) and information coming from short model construction (and future test). Some details of the short model as shown in the present paper could differ from the final design of D2 magnet.

Fig. 5 shows the longitudinal cross section of the short model and Fig. 6 shows a 3D view of the magnet connection side. As before mentioned, the magnet geometrical length is 1600 mm, however considering the plates for the longitudinal pre-stress and the space needed for cable splices, the overall length results to be 1830 mm. The magnetic length is 1350 mm. Since the short model will be tested in a vertical cryostat, it will be suspended to an intermediate flange through four tie rods (protruding from the flange in Fig. 6).

IV. STUDY OF CRITICAL COMPONENTS AND OPERATIONS

In this section, we report on the studies performed in the framework of the model construction about a couple of specific aspects of the design, namely the integration of the collared coils in the Al-alloy sleeves and the developments of the end spacers.

A. Integration into the Al-Alloy Sleeves

In order to better explain the mechanical integration of the collared coils into the sleeves, it is necessary to summarise some mechanical aspects of the design. The mechanical structure of the D2 dipole was designed to be able to withstand the Lorentz



Fig. 7. Lorentz forces sketch of D2 dipole magnet.

forces that arise when the magnet is energised up to 108% of the nominal current. In particular, the magnetic field in the two adjacent apertures being concordant, these apertures tend to repel one to each other, making the design more challenging with respect to the standard bending dipoles. The Lorentz forces acting in the magnet are schematised in Fig. 7. The horizontal resultant corresponding to the unbalance between the left and right branch of each coil is Fx = FxA - FxB = 196 kN/m, where FxA = 1347 kN/m and FxB = -1151 kN/m. Vertically, the Lorentz forces in the two branches act in the same direction and the resultant is Fy = FyA + FyB = 854 kN/m, where FyA = -437 kN/m and FyB = -417 kN/m.

In order to keep the two apertures in the right position despite the high horizontal force, two solutions can be envisaged. The straightforward way is to adopt the same collar for both apertures, so that the collar itself ensures the correct positioning of the apertures. However, this solution has several drawbacks with respect to the single collaring of each aperture: it requires a much larger and more expensive press, it makes the collaring operation intrinsically riskier and, in case of problems, it involves the de-collaring of both the apertures instead of a single one. For these reasons, we decided to collar separately each aperture. Then, another solution to keep the horizontal Lorentz force had to be introduced. Taking advantage of the fact that the window in the iron yoke hosting the coils is rectangular, we designed squared collars, as large as the warm inter-beam distance (188.7 mm, see Fig. 2) and around them, rectangular Al alloy sleeves, as shown in Fig. 2, whose function, exploiting the different thermal contractions during cool-down, is to keep strictly side by side the apertures. Three features have to be highlighted:

- the required coil azimuthal pre-stress at room temperature was determined looking for continuous contact between the winding pole and the collars even when the winding is energized at 108% of the nominal current. According the FE mechanical analyses the required average azimuthal pre-stress compression was fixed to 70 MPa after collaring. The magnetic design has consequently been optimized using the conductor dimensions at 70 MPa.
- 2) the laminated collars, 3 mm thick, have removable solid poles, 90 mm thick. Actually in this way, we involve only one single type of collar, perfectly left-right symmetric in the pole region, simplifying the design and generally reducing the costs (only one blanking die is needed). The asymmetry of the coils is completely included in the pole design, which, differently from the collars, can be rotated during assembly to be always in the correct position;

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Fig. 8. The mock-up developed for simulating the integration of the collared coils into the Al-sleeves. The collars of each aperture are made of 3 mm thick stainless steel plates machined by spark erosion. The Al-alloy sleeves were obtained by spark erosion too.



Fig. 9. The Al-sleeves are piled around the mock-ups of the collared coils. Here the operation done vertically is shown. Exercises of the operation in horizontal were successfully done as well.

3) the Al sleeves are solid pieces 100 mm thick. To ensure the success of the integration of these sleeves around the collared apertures, we left a total vertical gap between collars and sleeves of 0.6 mm (0.3 mm per side) and a total horizontal gap of 0.4 mm (0.2 mm per side). These gaps have been optimized considering that the collars, once the collaring pressure is relieved, relax themselves and increase of 0.15 mm per side vertically and of 0.08 mm per side horizontally.

As discussed in [5] and supported by FE computations, the gaps between Al-sleeves and collars are only present at room temperature. When the magnet is cooled down to 1.9 K, the Al-sleeves contract more than the collared coils compressing and holding them in the right position also during energization. To be noted that the reciprocal positioning of the two collared coils is guaranteed by two stainless steel keys as shown in Fig. 2.

The small gap between collared coils and sleeves could be an issue to the integration. For checking the feasibility of the mechanical integration, a mock-up, shown in Fig. 8, was designed



Fig. 10. End spacers. On the left the spacers as designed; on the right the spacers as they appeared after the 3D printing (still enclosed in the removable supports).



Fig. 11. A detail of the winding test. The asymmetry of the spacers requires different winding parameters to be used for left and right side.

and constructed with a gap of 0.2 mm all around the collared coils. The integration test performed on the mock-up (Fig. 9) confirmed the feasibility of the operation, which can be further smoothened by warming up the sleeves to $100 \,^{\circ}$ C, for increasing the gap.

B. Coil Ends

The coils of D2 magnet are asymmetric, causing some complications in the winding operation and requiring attention in the end spacer design. Usually the end spacer shapes of the nonconnection side are by far simpler to manufacture than the ones of the connection side. In this case, both end spacers are difficult because of the existing asymmetry. In order to design optimal end spacers not only for magnetic field quality but also to the aim of winding feasibility we preliminarily designed with Roxie [6] and constructed end spacers (see Fig. 10) with a 3D printer to be used only for winding test. In fact the used material is a thermoplastic polymer not suitable for cryogenic applications. The final end spacers will be done in G11.

The winding test campaign took about one month and showed that only a couple of spacer could be modified. Fig. 11 shows a detail of coil end during winding tests.

V. CONCLUSION

The development of the separation/recombination dipoles D2 for the High Luminosity upgrade of LHC moved from design to model construction phase. The engineering design has required some design changes and has underlined some critical operations, requiring specific experimental and industrial studies for collared coil integration and coil ends. The construction of the model is planned to be completed within spring 2018. It will be followed by the construction of a full length prototype, presently under engineering design phase, which is taking advantaged from the lessons learned with the short model construction.

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