Preliminary Design of the Recombination Dipole for Future Circular Collider

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***Abstract*—The Future Circular Collider (FCC) project aims at producing a conceptual design of a post-Large Hadron Collider (LHC) particle collider, able to reach higher beam energy with higher luminosity both for proton–proton and electron–electron configurations. In the proton–proton configuration, the FCC must be able to circulate 50 GeV protons in a 100 km tunnel. A key role in this project is played by the R&D on superconducting magnets, which must be able to produce magnetic fields significantly higher than in the LHC. Beside the bending dipoles, which must produce a 16 T field, also the multiplets in the interaction regions represent a technological challenge: as an example, the recombination dipoles are expected to produce a field of 10 T and therefore Nb_3Sn must be used. In this contribution, the preliminary design of a double aperture recombination dipole for the FCC will be presented in details. It features a two layers, cosine–theta design, in order to produce the required field of 10 T in the bore. The magnetic field has the same direction in both apertures, generating a not negligible crosstalk which is minimized using asymmetric coils. The magnetic design will be described, focusing on the main features of the Nb_3Sn conductor. The winding configuration and the iron yoke shape have been optimized to achieve a suitable field quality. A solution for the mechanical design will also be presented: the necessary prestress will be given by the so-called “bladder and keys” concept, which avoids the collaring and allows to obtain, thanks to differential thermal contraction of the components, most of the prestress after the cool down, when the Nb_3Sn is less brittle. The proposed solution fulfills all the standard requirements both from the magnetic point of view, i.e., field quality and current margin, and from the mechanical one, with a viable construction schema and reasonably low stress on conductor and support structures, during all the magnet operations.**

***Index Terms*—FCC, accelerator dipoles, superconducting magnets, Nb_3Sn.**

I. Introduction

THE Large Hadron Collider (LHC) at CERN is the largest and most powerful particle collider ever built: his lifespan will cover over 20 years through several center of mass energy and luminosity upgrading steps. More than ten years of activity are expected for LHC since now, however preliminary studies are ongoing for the construction of the next generation circular accelerator, namely the Future Circular Collider (FCC) [1]. These studies look at developing a conceptual layout and all the relevant skills for the project definition of a proton accelerator able to reach a center of mass energy of 100 TeV, almost an order of magnitude higher than LHC.

Among the technical improvements needed for this project, the construction of dipole magnets able to generate a stable 16 T magnetic field in a 50 mm bore is mandatory. This field allows to reach the energy goal with a 100 km long accumulation ring. Beside the bending dipoles, the separation/recombination dipoles are expected to produce a field of 10 T.

LHC superconducting magnets are accelerator magnet state of the art nowadays: they are based on Rutherford type cable made of copper and niobium-titanium alloy (NbTi), and they provide an 8 T magnetic field. This superconductor cannot provide the operating field for FCC, therefore the development of dipoles based on another low critical temperature superconductor, niobium-tin (Nb_3Sn) is needed: this material features a significantly higher critical field, but needs a complete redefinition of the construction process. In particular, Nb_3Sn must be thermally treated at high temperature, up to 900–1000 K, to get the correct intermetallic compound, and after the treatment the superconductor gets brittle and can hardly be bent without damages.

In this contribution we present the preliminary design of a double aperture cosine-theta separation/recombination dipole for FCC. We will refer to this magnet shortly as Double Aperture Recombination Dipole, (DARD). The design is based on the study for a cosine-theta bending dipole for FCC-HH developed by INFN [2], [3] and shares with that several features. The Nb_3Sn Rutherford cable, properly dimensioned, allows for a 10 T field in a 60 mm bore, resulting in an integrated magnetic field of 122 T·m, with the same polarity in the two apertures. In this design the interbeam distance is 204 mm and an asymmetric distribution of the conductors has been optimized to cope with the cross-talk between the two apertures.

II. Optimized Magnetic Design

The baseline parameters given by the FCC project for FCC DARD are shown in Table I. Based on previous experiences, i.e., LHC D2 [4] and HL-LHC MBRD [5], [6], we moved toward a layout of the windings with a left/right asymmetry, an elliptical

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TABLE I
BASELINE PARAMETERS OF FCC RECOMBINATION DIPOLE

Characteristics	Unit	Value
Integrated field strength	T·m	122
Magnetic length	m	12.2
Aperture	mm	60
Interbeam distance	mm	204
Operating temperature	K	1.9
Margin on load line	%	26.3
Field harmonics		< 10 units
Bore field	T	10
Conductor material		Nb_3Sn

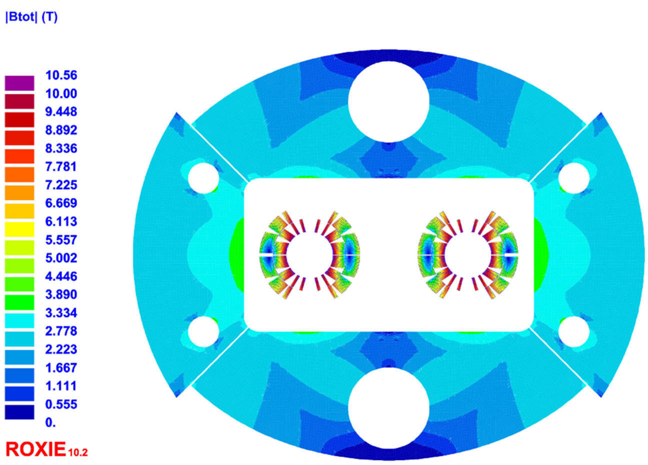

Fig. 1. Overview of the cross section of the optimized magnetic design.

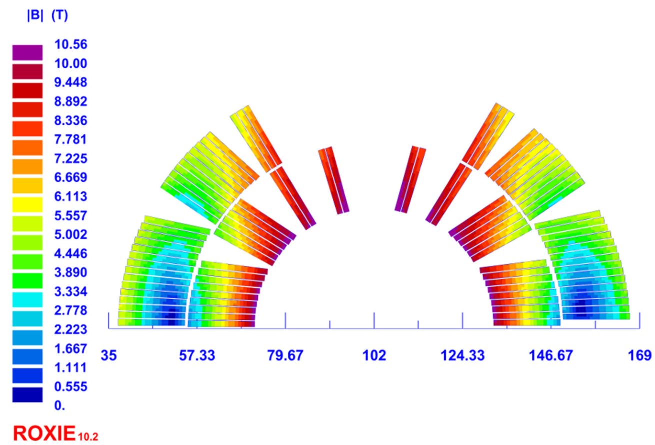

Fig. 2. Coil windings.

iron yoke and a rectangular window for the iron yoke in which the coils are installed. The simultaneous optimization of all the geometrical parameters of these components is needed to suitably compensate the magnetic cross-talk in order to obtain a field quality that completely fulfills all the project requirements. In particular, the optimization proved that an elliptical iron yoke is mandatory to reach this goal.

Fig. 1 shows the overview of the cross section of the cold mass with the calculated magnetic field superimposed, and in Fig. 2 the cable distribution in the winding is shown in more detail. In Table II the main characteristics of the optimized magnetic design are listed.

The magnetic cosine-theta layout is based on two asymmetric apertures with an interbeam distance of 204 mm and a bore diameter of 60 mm. To have a magnetic field of 10 T in the bore, two layer of conductor are required. The main features of the conductor used for this preliminary design are listed in Table III.

The magnetic optimization and harmonic analyses was performed using ROXIE [7] code. High order harmonics at the operating current are listed in Table IV, while field multipoles as a function of current are shown in Fig. 3. All harmonics stay well within the limits and the field quality of this optimized magnetic design completely fulfills all the requirements imposed by the project.

TABLE II
MAIN CHARACTERISTICS OF THE OPTIMIZED MAGNETIC DESIGN

Characteristics	Unit	Value
Peak field	T	10.56
Operating current	A	14680
Stored energy at nominal current	MJ/m	0.8
Yoke major semi-axis	mm	330
Yoke minor semi-axis	mm	265
Inductance at nominal current	mH/m	7.5

TABLE III
CONDUCTOR FEATURES

Characteristics	Unit	Value
Strand diameter	mm	0.8
Number of strand		40
Bare width	mm	16.8
Bare thin edge thickness	mm	1.376
Bare thick edge thickness	mm	1.610
Insulation thickness	mm	0.15
Keystone angle		0.8°
Cu/NCu		2.1
Operating current	A	14680
Margin on load line	%	26.3

TABLE IV
HIGH ORDER HARMONICS AT OPERATING CURRENT

b2	b3	b4	b5	b6	b7	b8	b9	b10
2.73	0.84	0.18	0.51	1.83	-1.31	0.08	5.37	-0.66

III. MECHANICAL ANALYSIS

The need for higher magnetic field and thus higher current leads to Lorentz forces higher than in present magnets. These forces could generate movements of the cables, which must be avoided to prevent local heating due to friction and, consequently, quenches. The strategy to avoid movements is to give a proper pre-stress to the coil, keeping in mind that, as already mentioned, Nb_3Sn cables are very brittle and their transport

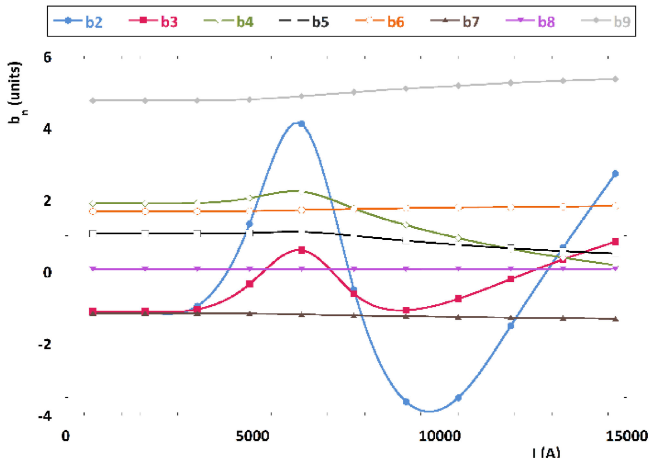

Fig. 3. High order harmonics as a function of current.

properties start to be deteriorated above 150 MPa at room temperature or 200 MPa at cryogenic temperature. So, giving the proper pre-stress to avoid movements and fulfill the stress limit requirements is very challenging and requires a careful study on the design. These requirements are particularly critical in the cosine-theta design, because the azimuthal distribution of the cable couples the horizontal and vertical components of Lorentz forces. On the other hand, all dipoles installed in particle accelerator so far are of cosine-theta type so this configuration is still considered as the baseline for future accelerator magnets.

The mechanical stability is provided with a proper pre-stress on the coil, which is usually given by a stainless steel collar surrounding the coils and closed under a press with some interference. Though this procedure is well established, it would work giving all the pre-stress during the assembly, i.e., at room temperature, when Nb_3Sn is more brittle. A new approach is then proposed for this magnet: the so called bladder and key technique [8]. The coils, collars and iron yoke complex will be inserted inside an aluminum shell and keys with some interference will be inserted in the gap between the iron yoke and the stainless steel pad, in the gaps opened by pressurized water bladders. In order to use the bladder and key technique it is necessary to adopt an iron yoke divided in four pieces to ensure the correct insertion of the bladders. In this way, during assembly, part of the pre-stress is given by the interference of the keys. Then, in the cool down, the aluminum shell shrinks more than the inner components, so that additional pre-stress is given to the coil at cryogenic temperature, when Nb_3Sn is less brittle.

The aim of this preliminary design is to guarantee the contact pressure between the pole turn and the titanium nose after energization at 10 T and ensure that each component of the structure stay within its stress limit during assembly, cool down and energization in order to prevent any degradation of the magnet performances.

In Table V the material properties and stress limit for each component of the model at room temperature (293 K) are reported, while in Table VI the same parameters are given at cryogenic temperature (1.9 K).

TABLE V
MATERIAL MECHANICAL PROPERTIES AT 293 K

Material	Stress limit [MPa]	E [GPa]	ν	α [$\cdot 10^{-3}$]
Coil	150		0.3	
• Radial dir.		30		3.1
• Azimuthal dir.		25		3.4
Austenitic steel (316LN)	350	193	0.28	2.8
Al7075	480	70	0.3	4.2
Ferromagnetic iron	230	213	0.28	2.0
Ti6Al4V	800	115	0.3	1.7
Wedges	270	100	0.3	3.37

TABLE VI
MATERIAL MECHANICAL PROPERTIES AT 1.9 K

Material	Stress limit [MPa]	E [GPa]	ν	α [$\cdot 10^{-3}$]
Coil	200		0.3	
• Radial dir.		33		3.1
• Azimuthal dir.		27.5		3.4
Austenitic steel (316LN)	1050	210	0.28	2.8
Al7075	690	79	0.3	4.2
Ferromagnetic iron	720	224	0.28	2.0
Ti6Al4V	1650	126	0.3	1.7
Wedges	> 300	110	0.3	3.37

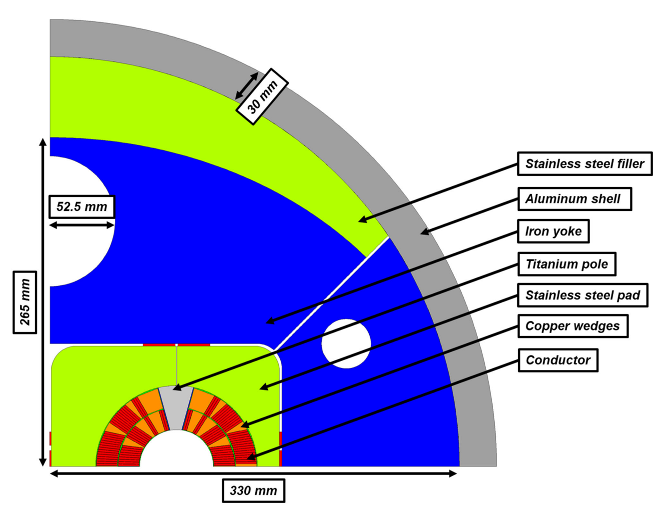

Fig. 4. Layout of the mechanical structure.

The mechanical analysis was performed using ANSYS [9] code and the optimized cross section of the mechanical structure is shown in Fig. 4. In particular, the finite element method was iteratively used in order to optimize the mechanical structure. In detail, position, length and interference of the keys and thickness of the aluminum shell were optimized using ANSYS model. Regarding the particular iron yoke design, it was adopted an

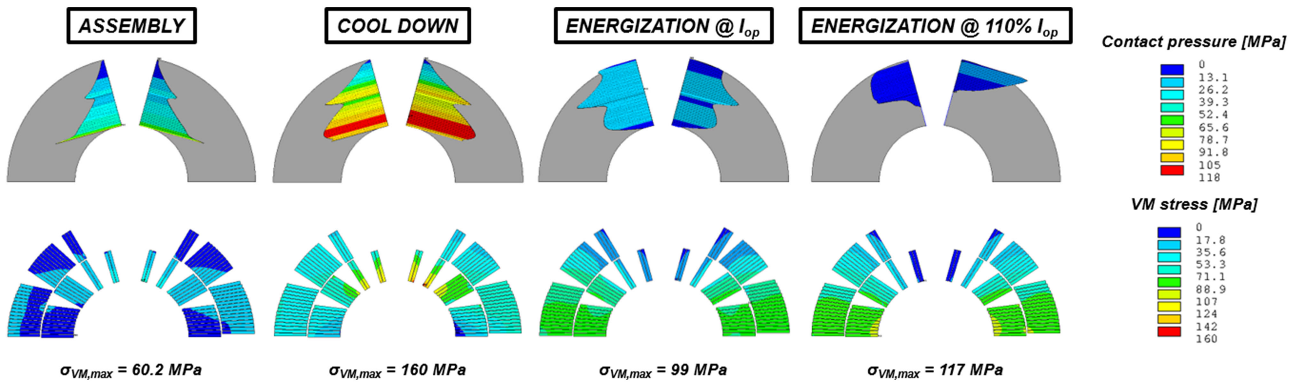

Fig. 5. Contact pressure and Von Mises stress distribution [MPa]: after assembly at room temperature; after cool down; after energization at operating current; after energization at 110% of operating current.

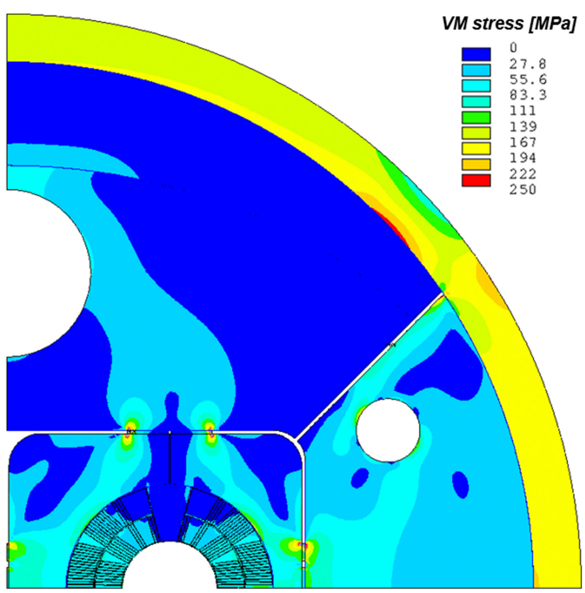

Fig. 6. Von Mises stress distribution [MPa] in the cross section of the magnet after energization at 10 T.

elliptical shape in order to fulfill the magnetic requirements. To guarantee an optimal match between the iron yoke and the external aluminum shell a stainless steel filler has been added.

The proposed preliminary design of the separation/recombination dipole for FCC widely fulfills all the project requirements regarding the contact pressure and the Von Mises stress distribution with no particular criticality. In Fig. 5 the contact pressure between pole and nose and the Von Mises stress distribution inside the winding after assembly, cool down, energization at 10 T and energization at 110% of operating current are shown.

The peak stresses are well below the limits in all conditions. It is worth noting that the mechanical structure is optimized to ensure that the contact pressure of the winding at the pole level is positive everywhere in operating conditions. At 110% of operating current, it is required that the peak stress remains within safe limit, but there is no additional requirement on the contact pressure.

Finally, the Von Mises stress distribution in the overall cold mass after energization is shown in Fig. 6.

IV. Conclusion

We have described a preliminary electromagnetic and mechanical design of the double aperture separation/recombination dipole for FCC.

The electromagnetic configuration of the magnet is based on two asymmetric apertures with an interbeam distance of 204 mm and a bore diameter of 60 mm. To reach a 10 T magnetic field in the bore, two layers of conductor are required.

The mechanical design is based on the bladder and key technique that guarantees the proper pre-stress to cope with Lorentz forces after the energization at 10 T.

The preliminary design proposed in this paper widely fulfills all the project requirements both from magnetic and mechanical point of view, featuring an acceptable peak field and load margin, a feasible manufactory scheme and reasonably low stress on conductor and support structures, after assembly, cool down and energization.

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