Electromagnetic and mechanical study for the Nb_3Sn cos-theta dipole model for the FCC

R. Valente, G. Bellomo, P. Fabbricatore, S. Farinon, S. Mariotto, A. Pampaloni, M. Prioli, M. Sorbi, M. Statera

***Abstract*—The Italian Institute for Nuclear Physics (INFN), in collaboration with CERN, is going to build the short model in Nb_3Sn of the main bending dipole for the hadron-hadron Future Circular Collider (hh-FCC). The magnet will be developed on the basis of the baseline design presented in the FCC Conceptual Design Report (CDR) in the end of 2018. In particular, it will be based on cosine-theta design, with an internal aperture diameter of 50 mm and a Bladder & Key configuration for the mechanics.**

The main purpose of the model construction is to demonstrate the feasibility of a magnet dipole with field quality characteristic suitable for a collider and magnetic field above the LHC frontier.The mechanical structure, which is a critical aspect of the magnet design, especially for the brittleness of the Nb_3Sn cables, will have to demonstrate the effectiveness to reach the highest performance achievable in terms of bore magnetic field.

Here we present both the electromagnetic and mechanical design study of the model.

***Index Terms*—Accelerator dipoles, superconducting magnets, Nb_3Sn, magnet design, finite element methods.**

I. INTRODUCTION

For the five-year period 2019-2023, CERN has signed an agreement with the INFN to construct the short model named Falcon Dipole, on the basis of the cosine-theta bending dipole design presented in the CDR of FCC [1], which is the final step of various configurations studied by the EuroCirCol collaboration [2], [3], [4]. In particular, the INFN groups in Milan (LASA laboratory) and Genoa are responsible for the design and the construction of the magnet, also involving Italian industrial partners. It will be a single aperture cos-theta dipole, which can reach a bore field of 14 T using two Nb_3Sn conductor layers, whose superconducting properties are needed to develop high field magnets, but still it is challenging in terms of mechanical design for accelerator magnets because of its brittleness. In this paper we describe the 2D design, focusing mainly on Rutherford cable parameters and coil layout. Moreover, we study how change the magnet performance using both the conductor in procurement from CERN available now and the EuroCirCol specs target conductor. The 3D coil ends preliminary study is mentioned and we also show a very preliminary quench heater configuration for the quench protection system. This work is completed with the detailed mechanical analysis which is crucial to determine the technical feasibility of the Bladder & Key technology [5] and therefore if the cold mass design satisfies the same requirements adopted by the EuroCirCol collaboration.

The Falcon Dipole is supposed to be one of the first steps towards the FCC main dipole construction. For this reason, the 16 T magnet presented as baseline for FCC [6] is taken as a reference for the Falcon design, keeping in mind that they are different in many aspects. In fact, the baseline main bending dipole for FCC is a twin-aperture magnet with a bore field of 16 T produced by a double pancake of an High Field conductor (two inner layers) and a Low Field one (two outer layers). On the other hand, the Falcon Dipole has only one aperture with a bore field of 14 T generated by a single pancake without grading of cable, i.e. there is the same cable both in the first layer and in the second one. Moreover, each aperture of the 16 T dipole has an asymmetric coil configuration to compensate the significant variation of the b_2 (not allowed) harmonic due to the strong interaction between the apertures. On the contrary, the INFN model maintains the symmetric coil layout since the magnet has one aperture. Finally, the two magnets have about the same cold mass diameter, but the model is much shorter (about 1.5 m instead of 15 m).

II. ELECTROMAGNETIC DESIGN

A. *Design parameters*

TABLE I
MAIN DESIGN REQUIREMENTS

Bore inner diameter	50 mm
Superconducting material	Nb_3Sn
Bore nominal field	14 T
Operating temperature	1.9 K
J_c (@ 4.2 K, 16 T)	1500 $\mathrm{A\,mm^{-2}}$
Operation on the load-line	86%
Maximum number of layers	2
Insulation thickness	0.15 mm
Cu/Non-Cu	≥ 0.8
Field harmonics	≤ 30 units
Number of apertures	1
Length	1.5 m
Hot Spot Temperature	350 K
Max Voltage toward Ground	1.2 kV

The Falcon Dipole has been designed using ROXIE 10.2 [7] to satisfy the parameters summarized in Table I, which are

---

G. Bellomo and S. Mariotto, M. Sorbi are with the University of Milan, Milan 20122, Italy and also with INFN-LASA, Milan 20090, Italy

M. Statera and M. Prioli are with INFN-LASA, Milan 20090, Italy.

P. Fabbricatore, S. Farinon and A. Pampaloni are with INFN-Genova, Genova 16146, Italy

R. Valente is with the University La Sapienza of Rome, Rome 00185, Italy and also with INFN-LASA, Milan 20090, Italy (email: riccardo.valente@mi.infn.it).

TABLE II
RUTHERFORD CABLE PARAMETERS

Superconducting material	Nb_3Sn
J_c (@ 4.2 K, 16 T)	$1500\ \mathrm{A\,mm^{-2}}$
Filament diameter (μm)	20
Cu/Non-Cu	1
Number of strands	34 (2 × 17)
Strand diameter (mm)	1.1
Bare height (mm)	19.8
Bare inner width (mm)	1.892
Bare outer width (mm)	2.065
Insulation thickness (mm)	0.15
Keystone angle	0.5°
Twist pitch (mm)	100

the EuroCirCol requirements, apart from the field harmonics constraint value. Since the main purpose of the model is to practise with the construction of a Nb_3Sn magnet, a higher priority is given to reach the bore field of $14\ \mathrm{T}$ with the simplest design possible, giving less importance to the field quality, which is less restrictive than the typical accelerator magnet requirements.

After the study of many Rutherford cable configurations, the conductor parameters summarized in Table II have been adopted, but the possibility they may change in the future is not excluded. Further conditions have been imposed on the coil layout to facilitate the winding procedure. More specifically, the minimum copper wedge thickness is set to be always above $1\ \mathrm{mm}$ to avoid cable damages, the alpha parameter of any conductor is chosen to hold the cable position approximately radial even at the cost of sacrificing the field quality and finally the minimum bending radius is kept of about $10\ \mathrm{mm}$, accordingly to the experimental data provided in [8].

B. Cross-section layout and magnet performance

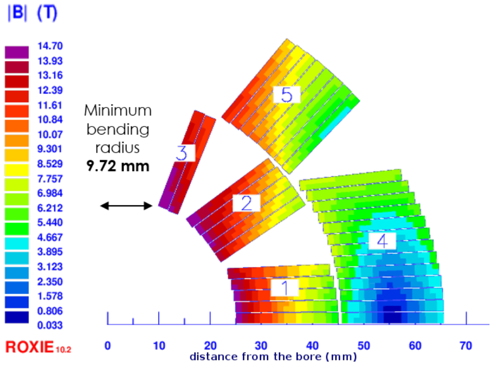

Fig. 1. One quarter of the coil arrangement, with insulated conductors.

The selected configuration is able to fulfil all the constraints described in Section II-A (see Fig. 1). The magnet has five blocks of conductors spaced from each other with copper wedges, of which the minimum thickness is of $1.08\ \mathrm{mm}$ between the block number one and two. The minimum bending radius is $9.72\ \mathrm{mm}$ near the block three. Regarding the iron yoke (in blue in Fig. 2), both the outer diameter of $700\ \mathrm{mm}$ and the squared aperture of side $180\ \mathrm{mm}$ are optimized for the Bladder & Key system, which is able to keep the stresses in the conductors under control (see Section III). Moreover, the yoke has two holes of $70\ \mathrm{mm}$ diameter for the cryo-system and other four holes of $20\ \mathrm{mm}$ diameter for the rods. Since we verified the holes location and size have no effect in the field quality, the whole configuration shown could change without this significantly affecting the electromagnetic features of the magnet.

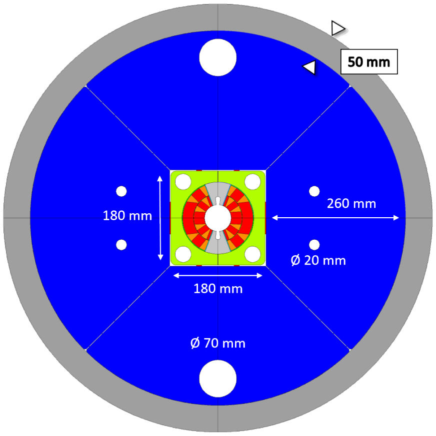

Fig. 2. Cross-section of the magnet cold mass.

An operating current of $25\ \mathrm{kA}$ has been set to achieve the bore field of $14\ \mathrm{T}$, with the operating point on the load-line of 14% margin as required. The harmonics analysis indicates that the short model satisfies the field quality requirement of $b_n \leq 30$ units both at injection and collision energy. The high order components of the 2D field are plotted in Fig. 3 as a function of the operating current, without considering any magnetization effect of the superconductor during the current ramp. The field quality at $25\ \mathrm{kA}$ is still not acceptable for Accelerator Physics standard, in particular because of b_5 and b_7 harmonics. Moreover, all the allowed harmonics has been integrated over the magnetic length of $1.5\ \mathrm{m}$ to study the field quality along the longitudinal direction: all the results are summarized in Table III. As mentioned before about the yoke, almost all the harmonics are independent from the iron saturation and the only way to improve the field quality is the coil arrangement. After recursive optimizations, we found the best cross-section layout for our purpose, namely a trade-off between high performances and geometrical constraints.

TABLE III
2D AND 3D HIGH ORDER HARMONICS AT OPERATING CURRENT.

Harmonics (units)	b_3	b_5	b_7	b_9	b_{11}	b_{13}
2D	1.28	-6.24	18.06	2.06	0.97	-0.72
3D (integrated)	3.12	-5.06	17.21	1.75	0.72	-0.74

The INFN model has been designed with the EuroCirCol target cable, whose high performances are parametrized by the critical current density of $1500\ \mathrm{A\,mm^{-2}}$ at $4.2\ \mathrm{K}$ and $16\ \mathrm{T}$ (see Table II). But we also study how the magnet

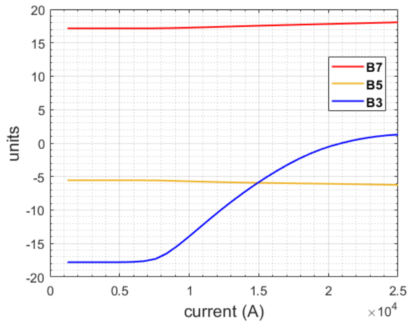

Fig. 3. Harmonics 2D analysis without magnetization effects of the superconductor.

performance changes using the conductor available at CERN now, which has a lower performance, i.e 1200 $\mathrm{A\,mm^{-2}}$ at 4.2 K and 16 T. The results of that comparison indicate the target field of 14 T could be reached with the lower performance conductor requiring a reduced margin of 9.5%. Moreover, the design proposed could theoretically reach 16 T in the bore increasing the current up to the short sample limit (SSL) of the EuroCirCol target cable (see Table IV).

TABLE IV
COMPARISON BETWEEN TWO DIFFERENT CABLE PERFORMANCES.

Conductor performance J_c (@ 4.2 K, 16 T)	Bore field (T)	Operating current (kA)	Margin on load line (%)
1500	14 / 16 / 16.2	25.0 / 28.9 / 29.3	14 / 1.3 / 0
1200	13.3 / 14 / 15.4	23.7 / 25.0 / 27.8	14 / 9.5 / 0

C. Coil ends design

In this paragraph we presented the first design of the coil ends for the return end side. There are still no specific constructive requirements, so the same criteria adopted for the FCC cos-theta dipole has been taken as a guideline. In particular, the length of the coil ends is requested to be kept below 300 mm and the margin must be larger than 14% also where the cable is bent.

In the design proposed the overall length of the magnet is about 1.7 m, of which the iron yoke occupies 1.4 m in the straight section. The conductor starts to bend 20 mm after the iron yoke edge and the coil end length is therefore 127.7 mm in total. In order to simplify the winding process, the two blocks of the second layer have been partitioned each in two sub-blocks. The minimum and the maximum longitudinal distance between the blocks are 10.3 mm and 59.4 mm respectively. The 3D model has been implemented in the ROXIE code and the electromagnetic analysis indicates that the peak field reached in the coil ends is 14.6 T (margin 14.5%), which is less than 0.1 T with respect to the peak field in the straight section (margin 14%).

D. Quench Protection

The construction of the INFN cos-theta model is the opportunity to test a quench protection system able to satisfy the EuroCirCol requirements, i.e 40 ms to detect the quench and activate the protection system, the maximum hotspot temperature below 350 K and the maximum voltage toward ground below 1.2 kV [9]. According to the EuroCirCol experience [10], [11], [12], two quench protection systems are candidates to be used in the next generation High Field accelerator magnets: one based on the Quench Heater (QH) system and the other one on Coupling-Loss Induced Quench system (CLIQ) technology [13].

For the INFN cos-theta model a preliminary analysis has been performed with QLASA software implementing a QH system, with the heaters installed on the external surface of the second layer for the whole length of the magnet. Moreover, the quench protection circuit is equipped with a dump resistor of 35 mΩ to easily extract the stored energy density of 0.68 $\mathrm{MJ\,m^{-1}}$ from the magnet. Using a voltage threshold of 100 mV and a delay time of 40 ms, the maximum hot spot temperature reached is 175 K before the current decays completely, with a maximum voltage of ±400 V towards the ground. The same study has been performed for the same magnet with a length of 15 m. In this case it is requested that the magnet is auto-protected (no dump resistor) and therefore additional quench heaters are needed to be installed in the internal surface of the first layer, in order to keep the hotspot temperature below 350 K.

III. MECHANICAL DESIGN

A. Mechanical constraints

The requirements adopted are the same set out in the EuroCirCol collaboration. First of all, the maximum Von Mises (VM) stress accepted in the conductors is 150 MPa at room temperature and 200 MPa at cryogenic temperatures, to prevent the risk of degrading the Nb_3Sn cable performance in terms of critical current density carried. Moreover, the VM stresses in the mechanical structure must always be below the yield strength of each material. Finally, in order to avoid any quench triggered by overheating due to movements between the coil and the pole, the averaged pole-coil contact pressure has to be larger than 2 MPa in pole-turns midpoint.

B. Mechanical design parameters

The main feature of this project is the Bladder & Key solution [5], which is a technique particularly appropriate in accelerator magnets with cables made of Nb_3Sn. Indeed, the interference generated by the keys provides part of the prestress at room temperature so that the stress in the conductors can be kept under the established threshold up to energization.

In Fig. 2 the cross section of the cold mass is shown with the main dimensions: in blue the four sectors of the iron yoke and in grey the aluminum shell 50 mm thick. The coils area is zoomed in Fig. 4 to better appreciate all the components of the Bladder & Key system. The coils are winded with the double pancake technique and impregnated. On the other hand, the titanium pole is in contact with the coil but they can slide and detach from each other. The keys are inserted between the iron yoke and the stainless steel pads opening a gap by inflating

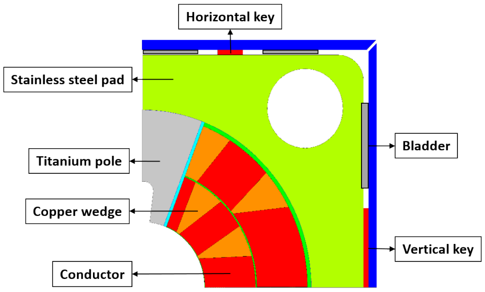

Fig. 4. Enlargement of the winding region.

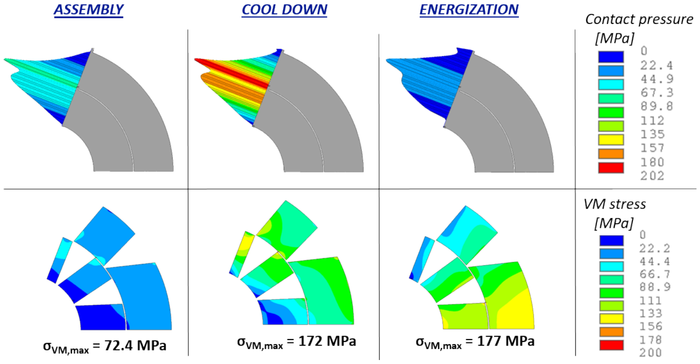

Fig. 5. FE analysis results at the nominal field of 14 T: in the first line the pole-coil contact pressure plot and in the second one the VM stresses in the coils, computed in the three simulation steps.

the bladders. The pre-stress at room temperature can be tuned with a specific key interference depending on the operating current chosen. The four sectors of the iron yoke are enclosed in an aluminum shell which provides an additional pre-stress during the cool down because of its higher thermal contraction with respect to the iron.

C. FE analysis and results

TABLE V
THREE LOAD CASES

Load cases	Bore field	Vertical key interference
Nominal field	14 T	0.5 mm
Cable in procurement short sample	15.5 T	0.6 mm
EuroCirCol cable short sample	16 T	0.7 mm

The mechanical model has been analysed with the FE code ANSYS [14] in three simulation steps:

- Assembly: the keys are inserted in the gap opened by the bladders with a pressure less than 30 MPa. The horizontal key has an interference of 0.1 mm and the vertical one depends on the operating current. On the basis of the comparison study between the two cable performances presented in Section II-B, three load cases has been studied: the nominal field of 14 T and the SSL of both the EuroCirCol cable and the cable in procurement from CERN (see Table V);
- Cool down: the magnet is cooled from room temperature to 1.9 K and therefore the contraction of each magnet component is simulated;
- Energization: the stresses due to the Lorentz forces are computed from each conductor element.

During all the simulation steps, it is assumed the sliding hypothesis between the titanium pole and coils with a friction coefficients of 0.2, and the same value is adopted between the keys, the iron yoke and the aluminum ring.

The results provided by the ANSYS simulation show that all the mechanical requirements are fulfilled at the nominal field of 14 T, which means the interference of the vertical key set to 0.5 mm (see Fig. 5). First of all, the pole-coil contact pressure is always positive on average, and where it is zero a gap less than 3.2 μm is opened, which is considered negligible. Then, the stress in the coils is always below the critical limit of 150 MPa at room temperature and of 200 MPa at cold. The maximum stress obtained is 177 MPa during energization, but in a very localized region. The VM stresses in each magnet element are not reported for simplicity, because they are well below the yield strength limits required.

Eventually, the same analysis has been performed for the other load cases, i.e a vertical key interference of 0.6 mm and 0.7 mm, which correspond to a bore field of 15.5 T and 16 T respectively. Since the mechanical design is optimized to work at the nominal field, the requirements are not satisfied completely, in fact the pole-coil contact is lost at energization and a gap less than 11.3 μm is opened in both scenarios. Regarding the VM stresses in the coils, a peak of about 200 MPa is reached for the 0.6 mm interference case and about 210 MPa for the 0.7 mm one. Therefore, a bore field of 16 T can be reached theoretically at the SSL of the FCC target performance conductor, but it is not really feasible.

IV. CONCLUSIONS

The starting point of our study is the cos-theta twin-aperture 16 T magnet, which is the baseline for the FCC CDR, issued in 2019 as the final product of the EuroCirCol experience. We presented a model cos-theta dipole which aims to achieve a bore field of 14 T, developing a design optimized to make the winding and assembly procedure as feasible as possible.

The magnet is able to reach 14 T in the bore within the margin of 14% on the load line, using the conductor with EuroCirCol specs and in principle the same field target may be reached using the conductor under procurement with lower performance, but with a reduced margin of 9.5%. Moreover, if the magnet is energized up to the short sample limit (EuroCirCol target cable) may achieve a bore field of 16 T. From the mechanical analysis it is clear the effectiveness of the Bladder & Key solution in keeping all the stresses below the limits, and in particular in the coils where the averaged stress is well below the Nb$_3$Sn degradation threshold, with a very localised peak of 177 MPa at energization. Finally, very preliminary results about the coil ends design and the quench protection system show that there is room for improvement in the next step of the project.

REFERENCES

[1] Future Circular Collider Study. Volume 3: The Hadron Collider (FCC-hh) Conceptual Design Report, preprint edited by M. Benedikt et al. CERN accelerator reports, CERN-ACC-2018-0058, Geneva, December 2018. Published in Eur. Phys. J. ST.

[2] M. Sorbi et al., “The Eurocircol cosine-theta Dipole Option for FCC”, IEEE Trans. on Applied Superc., Vol. 27, no. 4, 2017, art. no. 4001205

[3] V. Marinozzi, G. Bellomo, B. Caiffi, P. Fabbricatore, S. Farinon, A. Ricci, M. Sorbi, M. Statera, “Conceptual Design of a 16 T cos θ Bending Dipole for the Future Circular Collider”, Applied Superconductivity IEEE Transactions on, vol. 28, no. 3, pp. 1-5, 2018.

[4] B. Caiffi, G. Bellomo, P. Fabbricatore, S. Farinon, V. Marinozzi, A. Ricci, M. Sorbi, “Update on Mechanical Design of a Cosθ 16-T Bending Dipole for the Future Circular Collider”, Applied Superconductivity IEEE Transactions on, vol. 28, no. 4, pp. 1-4, 2018.

[5] S. Caspi, S. Gouraly, R. Hafalia, A. Lietzke, J. ONeill, C. Taylor, A. Jackson, “The use of pressurized bladders for stress contol of superconducting magnets”, Applied Superconductivity IEEE Transactions on, vol. 11,6948843, 2002.

[6] Valente, Riccardo, et al. "Baseline Design of a 16 T $\cos\theta$ Bending Dipole for the Future Circular Collider." IEEE Transactions on Applied Superconductivity 29.5 (2019): 1-5.

[7] S. Russenschuck, Field Computation for Accelerator Magnets: Analytical and Numerical Methods for Electromagnetic Design and Optimization. Weinheim, Germany: Wiley, 2010.

[8] Pulikowski, D., et al. "Windability tests of Nb 3 Sn Rutherford cables for HL-LHC and FCC." IEEE Transactions on Applied Superconductivity 28.3 (2018): 1-5.

[9] E. Todesco, “Quench limits in the next generation of magnets” CERN Yellow Report 2013-006 10-16 (2013).

[10] V. Marinozzi et al., “Quench Protection Study of the Eurocircol 16 T Cosθ Dipole for the Future Circular Collider (FCC)”, IEEE Trans. on Applied Superc., Vol. 27, no. 4, 2017, art. no. 4702505

[11] J. Zhao et al., “Mechanical stress analysis during a quench in CLIQ protected 16 T dipole magnets designed for the future circular collider”, Physica C: Superconductivity and its Applications Volume 550, 15 July 2018, Pages 27-34, https://doi.org/10.1016/j.physc.2018.04.003

[12] T. Salmi et al., “Quench Protection of the 16 T Nb3Sn Dipole Magnets Designed for the Future Circular Collider”, presented at this Conference 3LPo2E-03 [L42], to be published at IEEE Trans. on Applied Superc., 2019

[13] Ravaioli, Emmanuele. CLIQ. A new quench protection technology for superconducting magnets. No. CERN-THESIS-2015-091. Twente U., Enschede, 2015.

[14] https://www.ansys.com/