Identification of preferred dipole design options and cost estimates: Deliverable D5.2

Tommasini, Davide (CERN) *et al.*

28 July 2017

The European Circular Energy-Frontier Collider Study (EuroCirCol) project has received funding from the European Union's Horizon 2020 research and innovation programme under grant No 654305. The information herein only reflects the views of its authors and the European Commission is not responsible for any use that may be made of the information.

The research leading to this document is part of the Future Circular Collider Study

Grant Agreement No: 654305

EuroCirCol

European Circular Energy-Frontier Collider Study

Horizon 2020 Research and Innovation Framework Programme, Research and Innovation Action

DELIVERABLE REPORT

IDENTIFICATION OF PREFERRED DIPOLE DESIGN OPTIONS AND COST ESTIMATES

Document identifier:	EuroCirCol-P2-WP5-D5.2
Due date:	End of Month 26 (August 1, 2017)
Report release date:	27/07/2017
Work package:	WP5 (high-field accelerator magnet design)
Lead beneficiary:	CERN
Document status:	RELEASE (V1.0)

Abstract:

This document contains a description of the preferred 16 Tesla dipole magnet baseline design with its expected performances. The document also includes an analysis of the individual merits and risks of the different, initial design options and gives a justification for the selection of the baseline design. The deliverable includes expected field levels, field errors and a cost estimate, which serve as input for the arc design consolidation.

The European Circular Energy-Frontier Collider Study (EuroCirCol) project has received funding from the European Union's Horizon 2020 research and innovation programme under grant No 654305. EuroCirCol began in June 2015 and will run for 4 years. The information herein only reflects the views of its authors and the European Commission is not responsible for any use that may be made of the information.

Delivery Slip

	Name	**Partner**	**Date**
Authored by	Davide Tommasini Fernando Toral	CERN CIEMAT	06/07/17
Edited by	Julie Hadre Johannes Gutleber	CERN	26/07/17
Reviewed by	Michael Benedikt Daniel Schulte Daniel Schörling	CERN	24/07/17
Approved by	EuroCirCol Coordination Committee		28/07/17

TABLE OF CONTENTS

1. INTRODUCTION

WP5 deals with the development and cost estimate of a superconducting dipole bending magnet design for the FCC hadron collider (FCC-hh).

This deliverable has been produced as a cooperative effort of all tasks in this WP:

- Task 5.1: Work package coordination (CERN);
- Task 5.2: Study accelerator dipole magnet design options (CIEMAT, CEA, CERN, INFN);
- Task 5.3: Develop dipole magnet cost model (CERN, CEA, CIEMAT);
- Task 5.5: Conductor studies (CERN, UNIGE, UT);
- Task 5.6: Devise quench protection concept (TUT, INFN, CERN).

This deliverable summarises the work documented in a large amount of supplemental material, all organized and accessible from the EuroCirCol website http://cern.ch/eurocircol under the WP5 as detailed below:

- The slides supporting the 24 video meetings performed in the frame of the WP5 are accessible in "Indico" from [1];
- The documents describing the design constraints and methods are accessible from [2];
- The Report of the 1st EuroCirCol WP5 review is accessible from [3];
- The papers presented at the Applied Superconductivity Conference 2016 in Denver (USA) are accessible from [4], and are detailed in [5-11].
- The talks given at the FCC week held in Berlin on May 2017 are accessible in [12].

Three design configurations have been explored:

1) **block-coils, 2) cosine-theta and 3) common-coils**.

All options have been explored considering the same assumptions, in particular concerning the magnet aperture (**50 mm**), the field amplitude (**16 T**), the conductor performance (assuming the availability of a conductor with a target critical current density of 1500 A/mm2 @ 4.2 K @ 16 T corresponding to **2300 A/mm^2 @ 1.9 K @ 16 T**), the margin on the load line (**>14 %**) and the allowed mechanical constraints on the superconducting coil (**<200 MPa** at cold).

An overview of these options has already been shown in deliverable D5.1, released in October 2016.

Since then, the effort has been devoted to redefine and optimize the options, also considering a possible use of such magnets in a High Energy Large Hadron Collider (replacement of the current flagship particle collider at CERN with new magnet technology, thus increasing the field strength of the bending magnets and eventually the collision energy significantly). This new requirement imposes a major constraint on the maximum allowed size of the cryostat to at most 1200 mm. A number of ideas to meet this requirement were discussed during the FCC week in Berlin (http://cern.ch/fccw2017) and have been further developed during two WP5 video meeting: Video Meeting 23 on June 20th and Video Meeting 24 on July 11th, accessible from the link https://indico.cern.ch/category/7119.

2. SUMMARY OF THE DESIGN OPTIONS

Three design configurations have been explored: 1) **block-coils**, 2) **cosine-theta** and 3) **common-coils**. Furthermore, an initiative for the exploration of a fourth option, the canted cosine-theta, has been initiated by Swiss (PSI) and US (LBNL) laboratories. The US laboratories are partners in the EuroCirCol project, the Swiss institutes are members of the FCC collaboration. This initiative is not further detailed in this document because it does today not represent a competitive option with respect to the three currently explored within EuroCirCol. The reason is the much higher conductor amount needed at the present stage of the design.

All designs are elaborated with the same assumptions on the conductor properties (availability of a conductor with a target critical current J_c of 1500 A/mm^2 at 4.2 K and 16 T, copper with RRR=100, maximum strand diameter of 1.2 mm, minimum Cu/nonCu of 0.8:1), the operational margin on the load-line for a nominal bore field of 16 T (14%, which means 18.6 T short sample bore field), the quench protection parameters (time delay of 40 ms, maximum hot spot temperature of 350 K, maximum voltage to ground of 1.2 kV due to the magnet and up to 2.5 kV including the circuit), the mechanical properties of the coils and in general the structural parameters of the materials used in the magnet.

In the conceptual design phase, the quench protection studies considered if the designs are protectable and for all designs the same quench protection method was assumed. Recently, detailed considerations on quench protection systems and the benchmark of the simulation tools have been carried through. Particular effort has been spent to design Coupling Loss Induced Quench (CLIQ) protection systems for the design options. Also a design for heater only based protection in addition to the combination of these two (quench heaters + CLIQ) has been devised. These detailed studies have confirmed that the assumptions taken in the initial conceptual design phase are valid (e.g. predicted quench delay is reasonable) and that CLIQ is a promising option to protect the magnets with adequately low voltages and hot spot temperature.

The cost model is accompanying the EuroCirCol study since the beginning and contributed to the finalization of the design parameters. For example, assuming that a target cost of the Nb_3Sn conductor of 5 EUR/kA·m at a target performance of J_c=2300 A/mm^2 at a magnet flux density of 16 T and at a temperature of 1.9 K can be obtained, it has been shown that the operation at a temperature of 1.9 K at a load line margin of 14 % and a magnet aperture of 50 mm represents an ideal combination for the baseline parameters. The cost model considers both an extrapolated approach from past projects, in particular from the LHC, and an analytical approach. Scaling the FCC-hh dipole magnet cost from LHC, taking the higher complexity and double number of coil layers into account, would yield a target cost for parts of about 400 kEUR/magnet (50% above LHC) and for assembly of about 500 kEUR/magnet (75% above LHC). To identify cost-effective production methods and materials for the different magnet parts detailed studies need to be performed in collaboration with industrial partners. Concerning the assembly costs the number of assembly lines and tools, such as for example the number of heat treatment ovens, reaction fixtures and impregnation moulds is being estimated, as well as the labour cost for each assembly step are considered, depending on the required production rate (tentatively 20 magnets/week to complete the production in 5 years). For infrastructure costs such as water, gas, electricity, maintenance, insurance, administrative and financial management a fixed 25% of direct tooling and labour assembly costs are added.

Considerations deriving from the cost model have been used, among others, in chapter 3 for the choice of the baseline option.

Since the beginning of the activity in July 2015, the project evolved considerably: In 2016 an adjustment of the conductor and load line margin parameters paved the way for electromagnetically efficient coil cross section designs of all design options. New features in the common coil design allowed to partially fill the gap of amount of conductor needed with respect to the cosθ and the block-coil configurations, and finally a similar effect has been obtained by introducing a new concept of canted-cosθ using large cables.

This year, thanks to a released constraint on the quadrupole field component produced by the cross-talk between the two magnet apertures, the inter-beam distance could be considerably reduced, for the cosθ and the block-coil from 250 mm down to 204 mm. Further reduction to even 194 mm -the value presently in use in the LHC- seems feasible but would pose further challenges. Furthermore, following the FCC Week in May 2017, a major reduction of the magnet dimension and weight has also been made possible by allowing a stray magnetic field of up to an amplitude of 0.2 T at the magnet cryostat surface.

In practice, since the write-up of the previous deliverable D5.1, all options have considerably evolved, in particular towards more compact designs aiming at a possible use in the existing LHC tunnel.

2.1. BLOCK-COILS

The present cross-sectional design of this option, compared to the one originally elaborated in 2015, is shown in Figure 1.

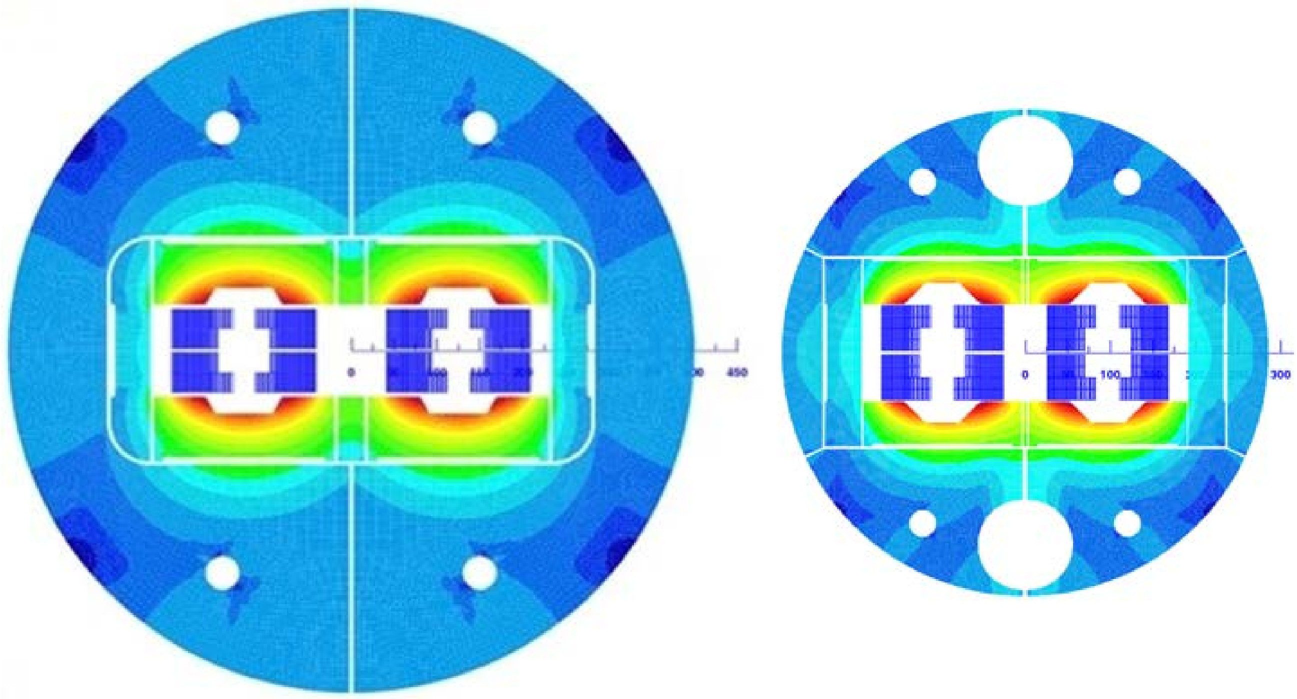


Figure 1: Cross section of the block design (left 2015, right 2017)

The total **amount of conductor required by this design is about 7860 tons**.

Each half magnet aperture features four decks composed of two 2-layers coils, an upper coil and a lower coil. Each coil is internally graded using 2 different cables: the inner cables use 21 strands of 1.1 mm diameter and Cu/nonCu ratio of 0.8, and the outer cables use 34 strands of 0.7 mm diameter and Cu/nonCu ratio of 2.0. The lower coil is made of 52 turns, the upper of 64 turns, the supply current is 10000 A and the magnet inductance (twin aperture) per unit of length is of 50 mH/m.

The mechanical structure is based on the key & bladder concept, featuring an aluminium shell providing the required coil-pre-stress increase between assembly and cold. The resulting coil stress distribution at the different assembly and operation steps are pictured in Figure 2.

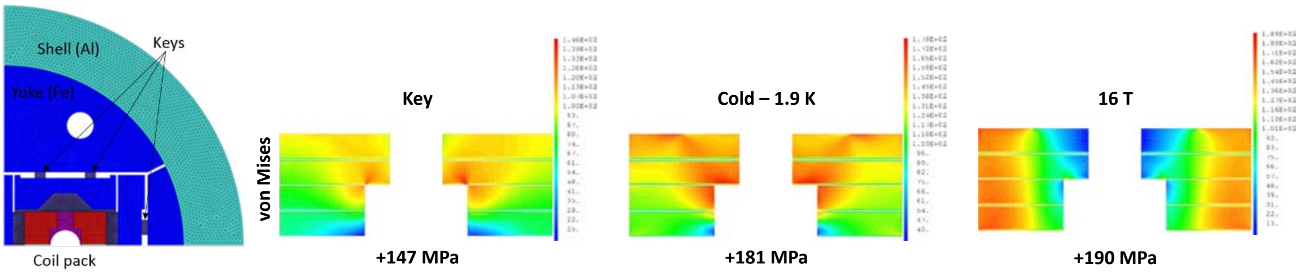


Figure 2: Mechanical model and stress distributions during assembly and energization.

Concerning the quench protection, the voltage and temperature distributions in the coil are pictured in Figure 3 assuming that the entire coil is quenched with a delay time of 40 ms; which can be achieved by using quench heaters, CLIQ or a combination thereof.

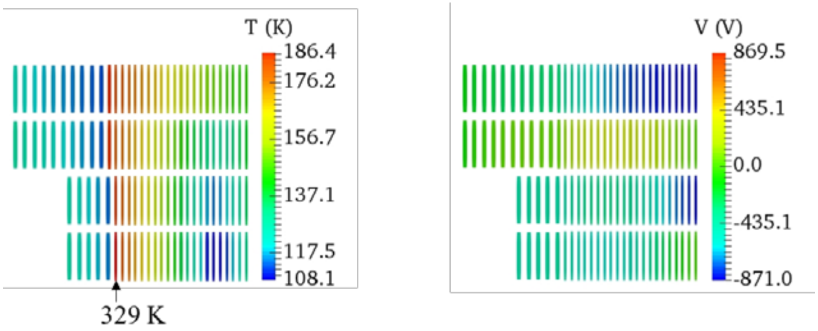


Figure 3: Quench protection: temperature and voltage distribution on the coil cross section.

2.2. COSINE-THETA

The present cross-sectional design of this option, compared to the one originally elaborated in 2015, is shown in Figure 4.

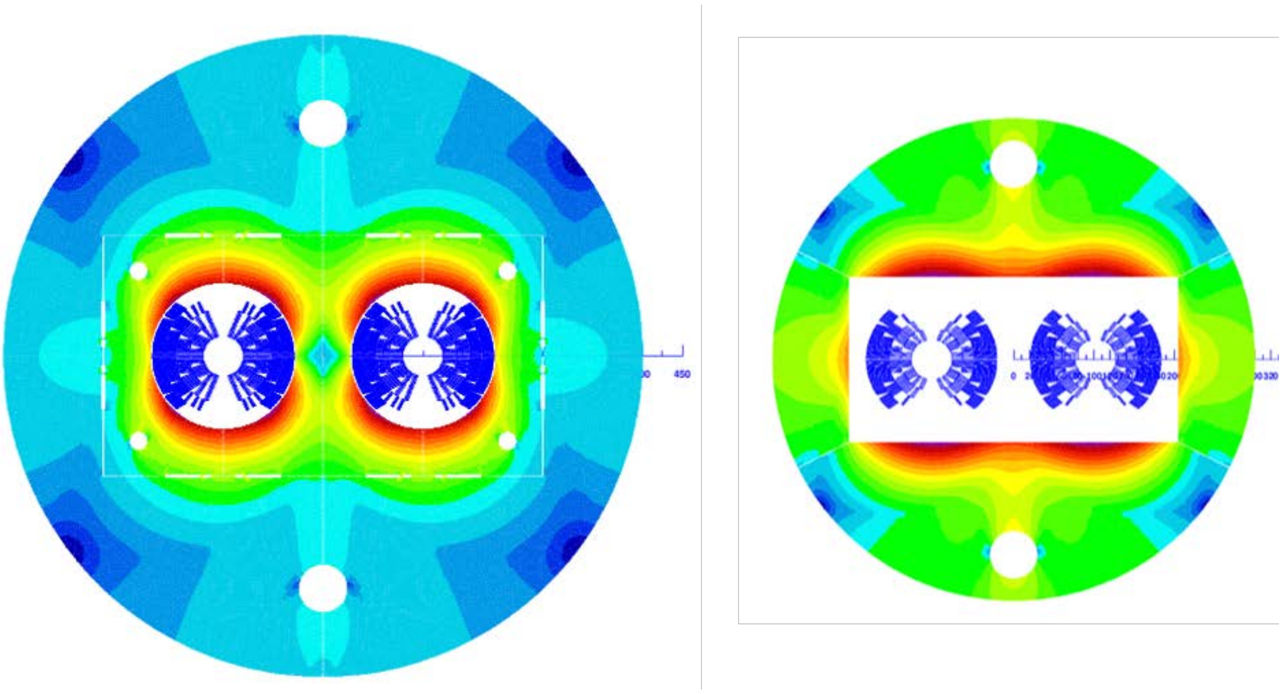


Figure 4: Cross section of the cosine-theta design (left 2015, right 2017).

The total **amount of conductor required by this design is about 7400 tons**.

Each half magnet aperture features two 2-layers coils made of 2 different cables: the two layers composing the inner coil use 22 strands of 1.1 mm diameter and Cu/nonCu ratio of 0.9, and the two layers composing the outer coil use 37 strands of 0.7 mm diameter and Cu/nonCu ratio of 2.2. The inner coil is made of 32 turns, the outer coil of 68 turns, the supply current is 11230 A and the magnet inductance (twin aperture) per unit of length is of 40 mH/m.

The mechanical structure is based on the key & bladder concept, featuring an aluminium shell providing the required coil-pre-stress increase between assembly and cold. The resulting coil stress distribution at the different assembly and operation steps are pictured in Figure 5.

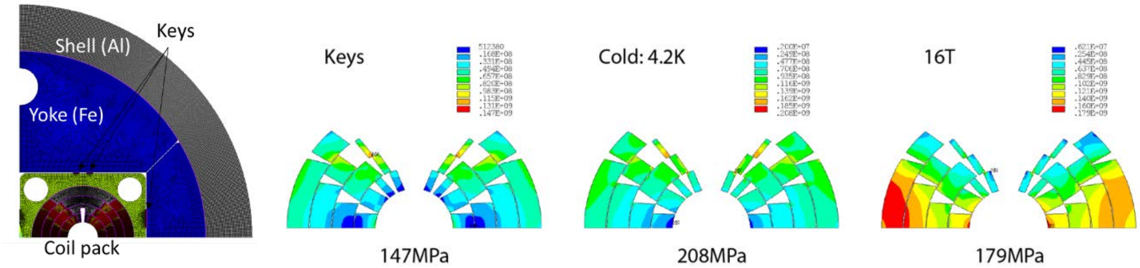


Figure 5: Mechanical model and stress distributions during assembly and energization.

Concerning the quench protection, the voltage and temperature distributions in the coil are pictured in Figure 6 assuming that the entire coil is quenched with a delay time of 40 ms; which can be achieved by using quench heaters, CLIQ or a combination thereof.

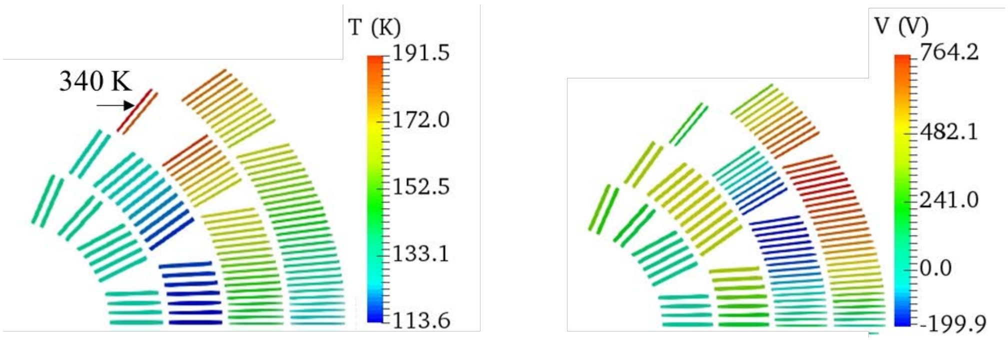


Figure 6: Quench protection: temperature and voltage distribution on the coil cross section.

2.3. COMMON-COILS

The present cross-sectional design of this option, compared to the one originally elaborated in 2015, is shown in Figure 7.

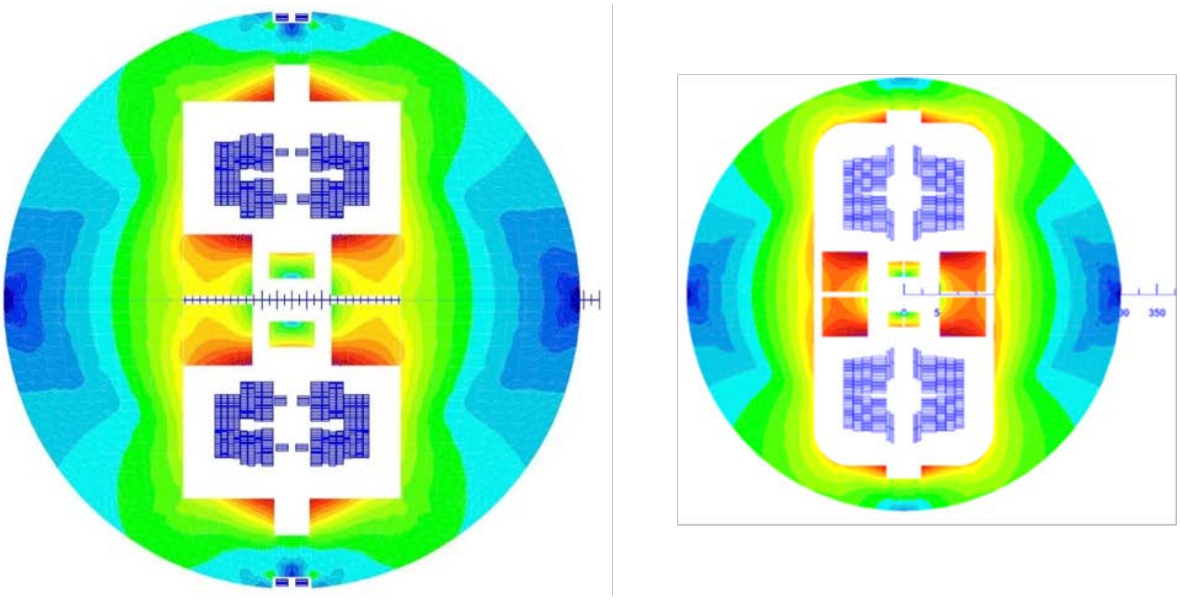
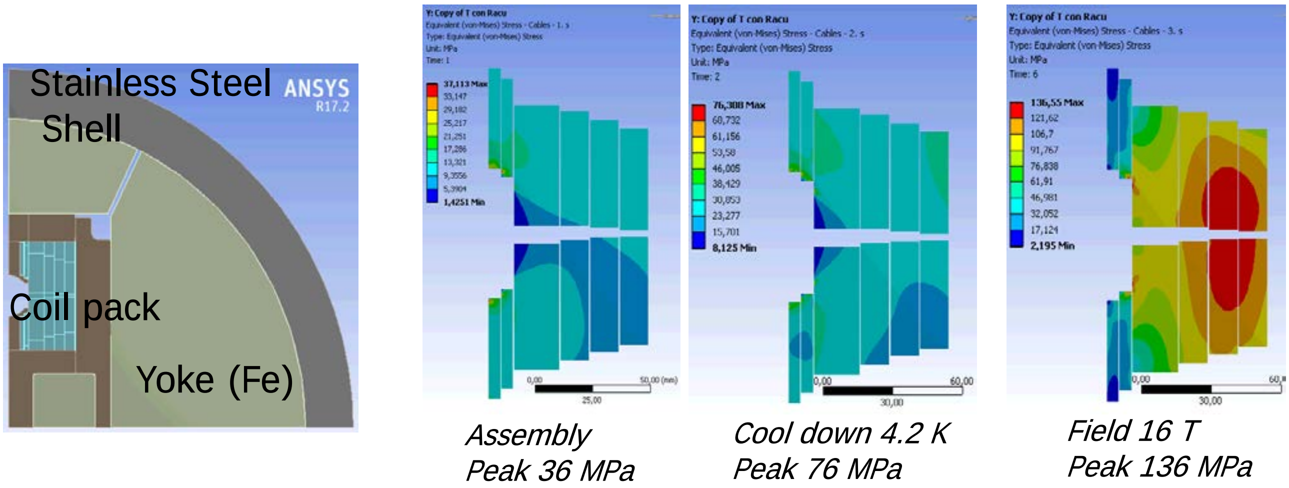


Figure 7: Cross section of the common-coil design (left 2015, right 2017).

The total **amount of conductor required by this design is about 9250 tons**.

In this configuration, the coils are shared between both apertures. Each magnet features four 2-layers main coils made of 3 different cables: the highest field layer is made with a cable of 30 strands of 1.2 mm diameter and Cu/nonCu ratio of 1.2, the other layer of the high field coils is wound a cable of 18 strands of 1.2 mm diameter and Cu/nonCu ratio of 2.5, while the low field coils are wound with a cable of 16 strands of 1.2 mm diameter and Cu/non Cu ratio of 2.5. Besides, there are four small double-layer pole coils using the same cable than the highest field layer of the main coils. The high field main coil is made of 39 turns per layer, the low field main coil of 77 turns, and the pole coils have 4 turns per layer. The supply current is 16100 A and the magnet inductance (twin aperture) per unit of length is of 24 mH/m.

The mechanical structure is based on a stainless-steel shell, which holds the Lorentz forces. Assembly is made by warming up the shell to allow the necessary gap for fitting around the coil pack. The resulting coil stress distribution at the different assembly and operation steps are pictured in Figure 8.



Assembly
Peak 36 MPa

Cool down 4.2 K
Peak 76 MPa

Field 16 T
Peak 136 MPa

Figure 8: Mechanical model and stress distributions during assembly and energization.

Concerning the quench protection, the voltage and temperature distributions in the coil are pictured in Figure 9 assuming that the entire coil is quenched with a delay time of 40 ms; which can be achieved by using quench heaters, CLIQ or a combination thereof.

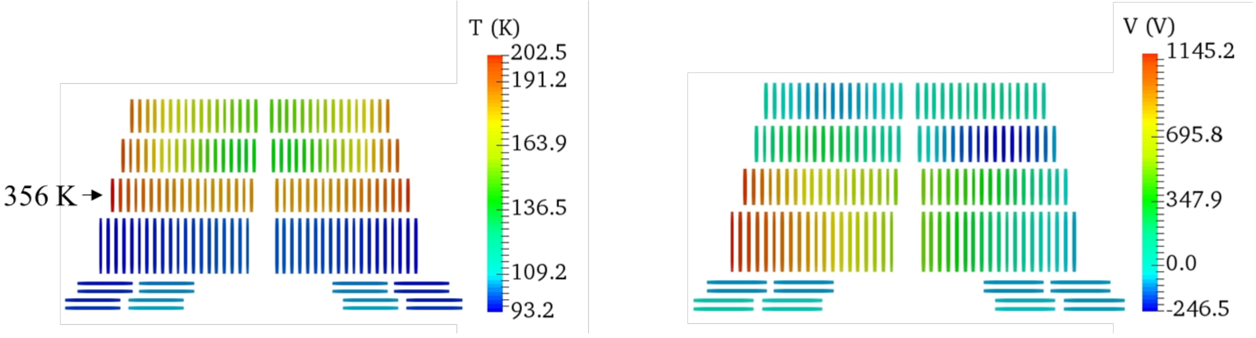


Figure 9: Quench protection: temperature and voltage distribution on the coil cross section.

3. CHOICE OF THE BASELINE OPTION

The work performed led to three designs that effectively work on paper, respecting all constraints imposed by the EuroCirCol project.

At the present stage of the knowledge, considering that none of these magnets has been built even in form of a short, simplified model, we have no elements to state that one particular design is technically superior to any other. Among the three designs, the common-coil option requires more than 25% additional conductor than the block-coil or the cosθ design. This represents, based on the present state of the cost model, a cost difference of about 10% at magnet assembly level, assuming that the parts and assembly is equal in cost for all design options. The performance of a common-coil configuration, constituted by “easy” racetrack coils, may possibly be more effective than the other designs, allowing to operate with less margin on the load line, enabling the design of more compact coils competing with block-coil or cosθ in terms of conductor use. However, this hypothesis cannot be supported by experimental evidence: a preliminary answer may only come once a first common-coil model magnet is built and tested. A definitive answer requires the construction of a number of models that permit a repeated consistent set of results. A first magnet is foreseen to be built and tested around 2021/2022, thanks to an initiative being carried out by CERN in collaboration with CIEMAT (Spain). Similar initiatives, in the same timeframe, are presently set up with INFN (Italy) for a cosθ, and with CEA (France) for block-coils.

It is remarkable how the EuroCirCol project triggers and motivates a considerable amount of supporting activities and initiatives going well beyond the EuroCirCol project scope.

Due to the lack of experimental evidence supporting the advantages of one particular solution with respect to the other, provided they all satisfy the WP5 constraints, and thanks to the quality of the designs elaborated so far, we decided to further explore in detail all options with an experimental construction and testing program.

Therefore, all options will be briefly described in the Conceptual Design Report. One option will be described in detail as a baseline.

Excluding the common-coil design due to cost reasons (with however the reserve mentioned above), the other two options, block and cosθ appear similar in terms of use of conductor, number of layers, electromagnetic and structural behaviour, with differences that are in a second order with respect to what can result from an experimental evidence, which is presently not available for this class of magnets.

We propose to select the cosθ design as the baseline to be described in the Conceptual Design Report, because this is the design in use in all superconducting colliders built so far: Tevatron, Hera, RHIC, and the LHC. All of them have operated or are operating close to or are exceeding their nominal performance. Although all these magnets are based on Nb-Ti, we have no reasons to believe that a similar design would not work for the FCC using Nb_3Sn, in particular if the constraints set for the magnet design are credible. On the other hand, we have no single example of any particle collider that uses other magnet configurations.

According to the present cost model the target cost for a 16 T magnet for FCC-hh built according to the cosθ design would be:

Conductor cost:	600 kEUR/magnet
Assembly cost:	500 kEUR/magnet
Parts cost:	400 kEUR/magnet
Total cost:	1.5 MEUR/magnet.

The calculation of the target conductor cost has been performed by assuming that the cost is insensitive to the Cu-amount in the strand. At a cost target of 5 EUR/kA·m at 16 T and 4.2 K a strand with a Cu/Non-Cu ratio of 1/1 and a density of 8700 kg/m^3 would cost ca. 450 EUR/kg. The non-Cu area in the cos-theta dipole cross-section is equal to 50 cm^2, resulting in an equivalent conductor mass (Cu/Non-Cu ratio 1/1) of 1.3 t/magnet and a target cost for the conductor of 600 kEUR/magnet.

4664 dipole magnets are required for FCC-hh. Assuming the same percentage of spare magnets as for LHC (around 3.6%) a total production of about 4830 magnets is required, yielding a total target cost of 7.2 GEUR for the dipole magnet system of FCC-hh.

4. CONCLUSION

The activity performed has led to the detailed development of three design options. Each of them fulfils the requirements and specifications set by for the FCC-hh particle collider and considers the possibility of a High-Energy LHC particle collider in the existing LHC tunnel using those magnet designs.

The lack of any experimental evidence that any of the existing design options would be technically superior to any other, cost considerations and past experience suggest that the design to be considered as the baseline for the Conceptual Design Report (CDR) should be the cosθ. The other options remain technically valid. They will also be briefly described in the CDR and are envisaged to be experimentally tested with short dipole model magnets.

The magnets feature a free physical aperture of 50 mm, a nominal magnetic field of 16 T with 14% of margin on the load-line when operated at 1.9 K, and meet all requirements set within the EuroCirCol project. According to the present state of the development of the cost model, the dipole system for the FCC would cost about 7.2 GEUR.

The selection of the cosθ as baseline for the CDR will be further discussed at an EuroCirCol project meeting on 9 and 10 October 2017 at CERN. The recommendation and rationale will be submitted for discussion to the 2nd WP5 international review, which takes place during this upcoming project meeting.

5. REFERENCES

1) http://cern.ch/go/C9rc
2) http://cern.ch/go/XP6X
3) http://cern.ch/go/Nc6m
4) http://cern.ch/go/Rr6t
5) Fernando Toral. Javier Munilla, Teresa Martinez, Luis Garcia-Tabares, “The EuroCirCol 16T common-coil dipole option for the FCC”, ASC 2016, Denver, Co, USA
6) Fernando Toral, Javier Munilla; Teresa Martinez ; Luis Garcia-Tabares, “EuroCirCol 16 T block-coils dipole option for the Future Circular Collider”, ASC 2016, Denver, Co, USA
7) Massimo Sorbi; Giovanni Bellomo; Pasquale Fabbricatore; Stefania Farinon; Vittorio Marinozzi; Giovanni Volpini, “The EuroCirCol 16T cosine-teta dipole option for the FCC”, ASC 2016, Denver, Co, USA
8) Vittorio Marinozzi; Giovanni Bellomo; Pasquale Fabbricatore; Stefania Farinon; Tiina Salmi; Massimo Sorbi; Antti Stenvall; Giovanni Volpini, “Quench Protection Study of the Eurocircol 16 T Cosθ Dipole for the Future Circular Collider (FCC)”, ASC 2016, Denver, Co, USA
9) Tiina Salmi; Antti Stenvall; Marco Prioli; Arjan P. Verweij; Bernhard Auchmann; Vittorio Marinozzi, “Suitability of different quench protection methods for the 16 T Nb3Sn accelerator dipoles designed for the FCC”, ASC 2016, Denver, Co, USA
10) Daniel Schoerling; Davide Tommasini; Fernando Toral; Teresa Martinez ; Maria Durante, ”Considerations on a cost model for high-field dipole arc magnets for FCC”, ASC 2016, Denver, Co, USA
11) Davide Tommasini et al., “ The 16 T dipole development program for FCC”, ASC 2016, Denver, Co, USA
12) FCC Week 2017, https://indico.cern.ch/event/556692

6. ANNEX GLOSSARY

SI units and formatting according to standard ISO 80000-1 on quantities and units are used throughout this document where applicable.

ATS	Achromatic Telescopic Squeezing
BPM	Beam Position Monitor
c.m.	Centre of Mass
DA	Dynamic Aperture
DIS	Dispersion suppressor
ESS	Extended Straight Section
FCC	Future Circular Collider
FCC-ee	Electron-positron Collider within the Future Circular Collider study
FCC-hh	Hadron Collider within the Future Circular Collider study
FODO	Focusing and defocusing quadrupole lenses in alternating order
H1	Beam running in the clockwise direction in the collider ring
H2	Beam running in the anti-clockwise direction in the collider ring
HL-LHC	High Luminosity – Large Hadron Collider
IP	Interaction Point
LHC	Large Hadron Collider
LAR	Long arc
LSS	Long Straight Section
MBA	Multi-Bend Achromat
Nb_3Sn	Niobium-tin, a metallic chemical compound, superconductor
Nb-Ti	Niobium-titanium, a superconducting alloy
RF	Radio Frequency
RMS	Root Mean Square
σ	RMS size
SAR	Short arc
SR	Synchrotron Radiation
SSC	Superconducting Super Collider
TSS	Technical Straight Section