Future Circular Collider

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Overview of magnet design options: Deliverable D5.1

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DELIVERABLE REPORT

OVERVIEW OF MAGNET DESIGN OPTIONS

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Abstract:

This document describes the design options for 16 T superconducting dipole magnets for the FCC hadron collider explored in the frame of the activities of WP5. All options have been considered under comparable assumptions and managed using the same tools to ensure a correct judgement and comparison of their relevant pros and cons.

Three baseline design configurations have been explored: 1) block-coils, 2) cosine-theta and 3) common-coils. A fourth option, the canted cosine-theta, has been initiated by Swiss (PSI, not part of EuroCirCol) and US (LBNL, EuroCirCol partner) laboratories.

The studies show that, adopting a reference margin to the load line of 14 % and with reasonable assumptions on the conductor performance, the total amount of conductor needed for the entire collider is between 7.5 and 10 ktons. depending on the option. The cosine-theta uses less conductor and the canted cosine-theta uses the largest amount.

The characterisation of the magnet design options is complete and the work to finalize and compare these options in the subsequent deliverable D5.2 (identification of preferred dipole design options and cost estimates) has started.

Delivery Slip

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1. INTRODUCTION

WP5 deals with the identification, elaboration and cost estimate of a bending magnet design for the FCC hadron collider. Within the scope of the same work package, a workable design of a demonstrator magnet model shall be developed.

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).

The activities performed to achieve the specific deliverables can be grouped in:
- Setting the magnets specifications;
- Establishing the tools (magnet design, quench protection, cost estimate);
- Exploring the magnet design options.

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 17 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].

Three design configurations have been explored: 1) **block-coils, 2) cosine-theta and 3) common-coils**. Furthermore, profiting of the preparatory work performed by WP5 in setting the magnets specifications and baseline parameters, an initiative for the exploration of a **fourth** option, the **canted cosine-theta**, has been initiated by Swiss (PSI) and US (LBNL) laboratories.

All options have been explored considering the same assumptions, in particular for the magnet aperture (**50 mm**), the field amplitude (**16 T**), the conductor performance (assuming a critical current density of **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).

The study quantified the main aspects of each design, which have to be considered in view of the comparative analysis of these options. This is the scope of the next deliverable D5.2 of WP5. In particular, the conductor amount needed for all accelerator dipole magnets would range from 7.5 ktons to 10 ktons depending on the design choice. Cosine-theta is the most effective and the canted-cosine-theta the less effective option in these terms. On the other hand, the cosine-theta imposes the highest stresses on the coil, and the canted cosine-theta the lowest.

2. SETTING THE MAGNETS SPECIFICATIONS

Setting the magnets specifications has been the first necessary step to develop the different design options on a common basis. The specifications are the result of the beam optics, vacuum and machine integration requirements, and of constraints to ensure a reliable performance.

The **requirements** consist of the **magnet length** and **field amplitude**, the **free physical aperture** where the vacuum chamber has to be fitted, and the **field quality** in a given good field region.

These requirements have been optimized through an intensive interaction with the "arc design WP2" and the "cryogenic beam vacuum system WP4", considering an efficient compromise between **contrasting targets**: **WP2** and **WP4 aim at the highest field amplitude** to maximize the space available for the experimental sections **and at the largest physical aperture** to incorporate the complex structured beam screen. The latter is removes synchrotron radiation and mitigates impedance, contributes to beam stability and lifetime. On the contrary, **WP5 aims at the lowest field amplitude in the smallest physical aperture** to reduce technical challenges and, most of all, magnet costs.

As an example of the work performed to achieve an efficient compromise, Fig.1 illustrates how the amount of conductor required for the 16 T dipoles depends on the magnet physical aperture.
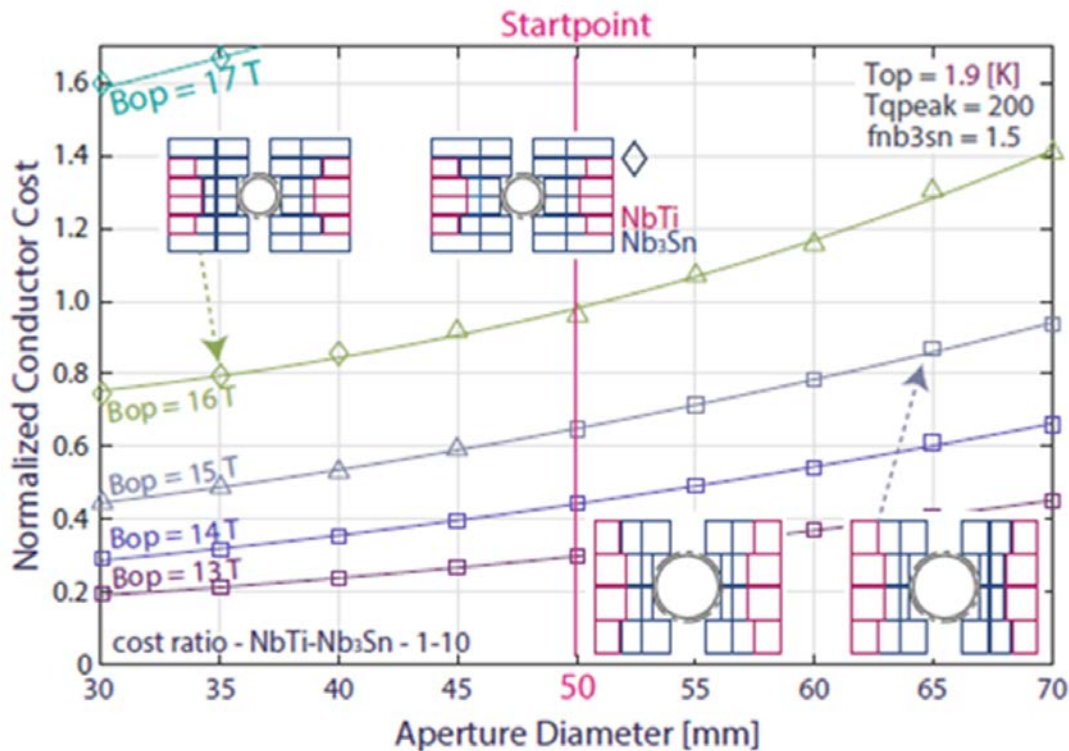

Figure 1: Normalised cost of conductor as a function of magnets physical aperture at different field strengths.

As a consequence of this process, the parameters have then been set to:

- **Field amplitude** : **16 T**
- **Physical aperture** : **50 mm**

A second group of parameters are related to the magnet design and are set to ensure the required performance. These parameters strongly depend on the characteristics of the superconductor, for which a number of hypothesis had to be set to specify a credible performance at the time the magnets have to be constructed. All parameters have been extensively discussed and iteratively reviewed in more than 15 video meetings of WP5, and specifically discussed and refined during the 1st EuroCirCol WP5

External Review, chaired by Steve Gourlay (LBNL), in May 2016 [Indico 516049, final report at http://cern.ch/go/Nc6m].

As an example of the importance of a correct assumption on performance parameters, Figure 2 illustrates how much the conductor amount depends on the margin on the load line considered for the magnets design. Figure 2 shows that decreasing the margin from an **initially "prudent" 18%** to a more aggressive, but **still credible 14%** allows **saving about 30%** of the conductor amount required for the production of the magnets.
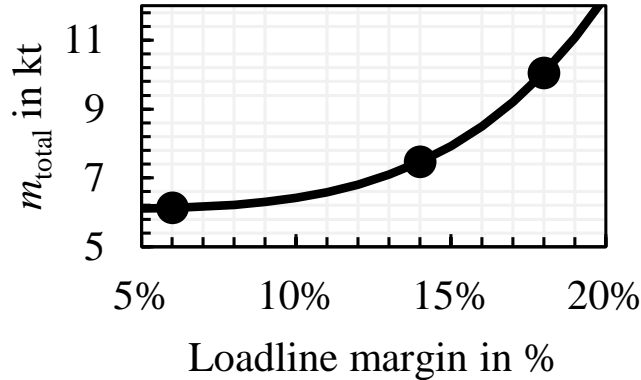

Figure 2: Amount of conductor required for the 16 T magnets as a function of the margin on the loadline.

Concerning the conductor performance, the critical current density I_c of the Nb₃Sn conductor is expressed by means of the following set of equations and plotted in Figure 3 at 1.9 K and 4.2 K operation temperatures:

$$
\begin{cases}
J_c = \dfrac{C(t)}{B} b^{0.5} (1-b)^2 \\
B_{c2}(T) = B_{c20}(1-t^{1.52}) \\
C(t) = C_0(1-t^{1.52})^{\alpha}(1-t^2)^{\alpha}
\end{cases}
$$

where t = T/Tc0 and b = B/Bc2(t) with B the magnetic flux density on the conductors. Tc0 = 16 K, Bc20 = 29.38 T, α = 0.96, C0 = 276000 AT/mm² are fitting parameters computed from the analysis of measurements on the conductor.

The conductor has the highest cost impact and is also directly related to the refrigeration costs as shown in Figure 3. Consequently, the operating reference temperature has been set to $\mathbf{T_{ref}= 1.9\ K.}$ The cabling degradation is assumed to be 3%.
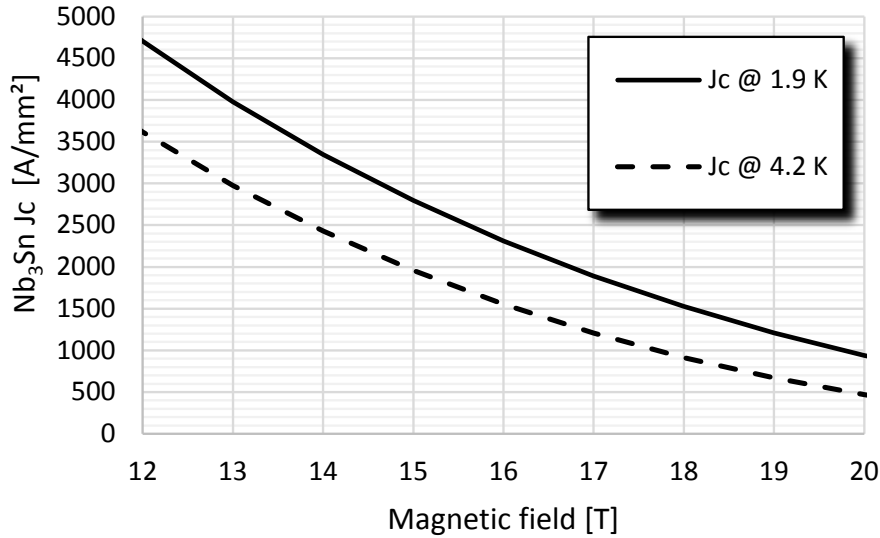

Figure3: Critical current density J_c at 1.9 K (baseline) and at 4.2 K.

The resulting magnet parameters are summarized in Table 1.

Parameter	Value
Reference magnet length	14.3 m
Free physical aperture	50 mm
Nominal bore field amplitude	16 T
Operating temperature	1.9 K
Margin on the load-line @ 1.9 K	>14 %
Critical current density @ 1.9 K, 16 T	2300 A/mm^2
Degradation due to cabling	3%
Cu/nonCu	>0.8
Hot spot temperature (@ 105% I_{nom})	<350 K
Strand diameter	<1.2 mm
Stress on the conductor @ 105% I_{nom}	<200 MPa
Voltage to ground (magnet only)	<1.2 kV
Total voltage to ground (incl. circuit)	<2.5 kV

Table 1: Salient magnets parameters

3. DESIGN TOOLS

All design options, though **carried out by different institutes, have been explored using the same tools**, in particular Opera® and Roxie for electromagnetic modelling, and Ansys® for structural modelling. Quench protection and cost estimates have been carried out in one specific task, to provide the most effective and homogeneous input to the design options.

3.1. QUENCH PROTECTION

Quench protection has been integrated into the magnet design from the beginning in order to ensure that the magnets will have a sufficient time margin for activating protection systems. The **required time margin** was the same for all magnet types: **40 ms**, consisting of **20 ms for detection** and **20 ms** for a protection system **to bring the coil to resistive state**. The estimation of obtainable protection system efficiency was based on the performance of quench heaters and/or CLIQ (Coupling-Loss Induced Quench system) with no limitations on their total energy and considering realistic technological improvements by the year 2030, the foreseen time of magnet fabrication. To evaluate the influence of the simulation method, the computations were compared with two different software packages, TALES and CoHDA + Coodi. In addition to the temperature profile in case of a quench as a function of the protection scheme and operation conditions, these tools also allow to compute and picture the distribution of voltage to ground in a coil cross section (see Figure 4).
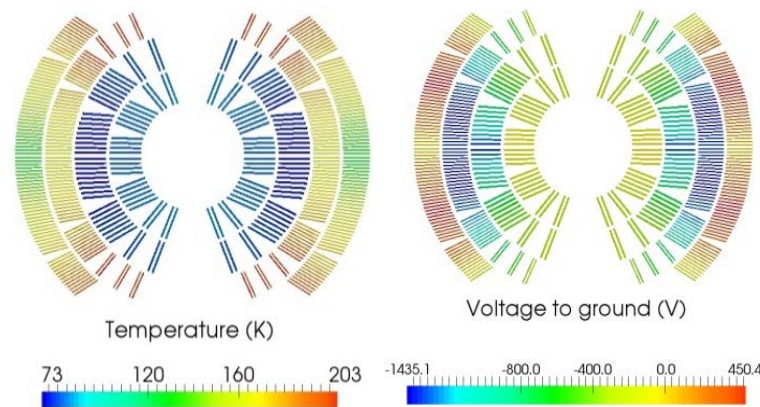

Figure 4: Example of plot of temperature distribution (left) and voltage distribution (right) in case of a quench.

3.2. COST ESTIMATE

An analysis of the cost drivers for the high-field magnets has been performed to include their impacts in devising good design specifications. This concerns in particular the technological choice of **superconducting material** (Nb$_3$Sn), the target **performance of Nb$_3$Sn** superconductor (Jc = 2300 - 3000 A/mm^2 @ 1.9 K and 16 T), the relevant **design margins** (14% loadline margin), the **aperture's** (50 mm), the choice of **operating temperature** (1.9 K), and the **nature and extent of grading** (two cable grading). The cost model will evolve with the study to better quantify the impacts and feed-back this information to the magnet designers.

4. MAGNET 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. This initiative is not further detailed in this document.

4.1. BLOCK-COILS

A large number of coil configurations with 2, 3 and 4 double pancakes per aperture has been explored: the best compromise in terms of conductor quantity and stress distribution resulted in a 4 double pancakes configuration. The cross-section with its 400 mm radius yoke is shown in Figure 5.
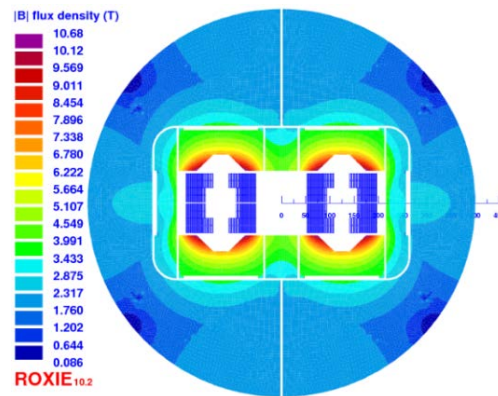

Figure 5: 2-in-1 block coil magnet cross-section within its iron yoke

Contrary to the cos-theta layout and its arch type configuration, coils of a block structure need to be internally supported. Here, a 6.3 mm thick bore is used to withstand the forces. This leads to a physical aperture of 62.6 mm instead of 50 mm in a cos-theta magnet. In Table II are reported the main parameters of the actual design. The design parameters of such a magnet is shown in Table 2.

Table 2: 2-in-1 block-coil magnet parameters.

Parameter	Values	Unit
Nominal current	10930	A
Peak field	16.81	T
Loadline margin	13.95	%
Inductance (2 apertures)	48.06	mH/m
Stored energy (2 apertures)	3016	kJ/m
Horizontal force (per ½ coil)	8473	kN/m
Vertical force (per ½ coil)	3572	kN/m
Bore thickness	6.3	mm
Mid-plane shim	1.45	mm
Hotspot	348*	K
Voltage to ground	1065*	V
Number of turns HF cable per layer	3+3+9+9 = 24	adim
Number of turns LF cable per layer	22+22+23+23 = 90	adim
Area of conductor (2 apertures)	151.9	cm²
Total weight**	8652	tons

The total **amount of conductor is about 8650 tons**, which is 20% lower than the quantity required with a previous baseline parameters before the May 2016 review. This is mainly due to the lowering of the loadline margin from 18% to 14% coupled to the decrease of the cnc ratio from 1.0 to 0.8.

The current magnet cross-section meets the requirements of the baseline in terms of field quality, protection Thotspot < 350 K, operating loadline margin and cable dimensions. For protection, a time of 40 ms is chosen between quench and total resistive coil transition.

The mechanical analysis of the WP5 ECC block coil magnet has been performed in a single aperture configuration. The outer diameter of the iron yoke is reduced by the 250 mm of the inter beam distance (800 mm – 250 mm = 550 mm). In order to contain the peak stress at warm on the coil below 150 MPa, bladder and key structure is used (Fig. 6): during cool-down of the whole structure increases the preloading due to the larger shrinkage of the outer aluminium shell with respect to the inner structure.
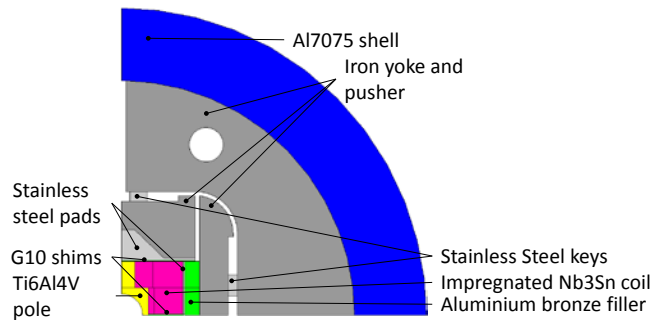

Figure 6: One fourth of the block-coils mechanical structure.

4.2. COSINE-THETA

The electromagnetic study of a cosine-theta design has been performed in the configuration of a double aperture inside the same yoke. In order to increase the efficiency of conductor and reduce the total quantity of superconductor, it is necessary to use a grading of the current density in the coils. For Nb$_3$Sn, the wind & react technology is mandatory because of the reduced conductor bending radius in coil end; the winding of the coils can be performed with the double-pancake technique, with the coil exits in the mid-plane and the inter-pancake jump in the pole region. For this reason, each conductor type requires at least two layers. Consequently, the cosine-theta solution requires a minimum of 4 layers, which is also the optimum in order to minimize the coil inductance and peak voltages during quench. The cross section optimizations have been performed mainly to minimize the conductor quantity, keeping the requirements of field quality and conductor maximum field margin on load line. The magnet cross-section in a double aperture configuration is represented in Figure 7.
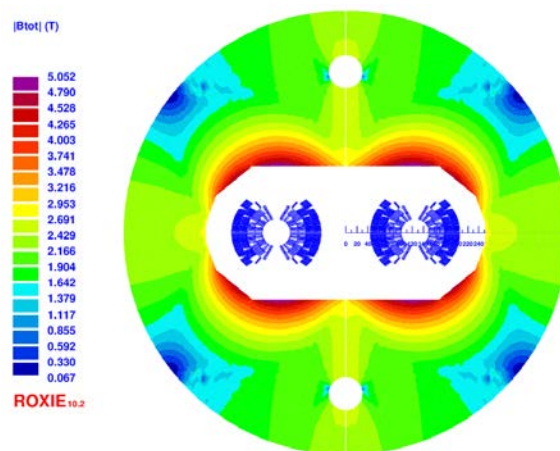

Figure 7: 2-in-1 cosine-theta magnet cross-section within its iron yoke.

The main parameters of the optimized design are reported in Table 3.

Table 3: Cosine-theta magnet parameters.

Parameter	Values	Unit
Strand diameter H.F./L.F.	1.1/0.71	mm
Strand number H.F./L.F.	22/36	
Bare cable inner thickness H.F./L.F.	1.892/1.204	mm
Bare cable outer thickness H.F./L.F	2.072/1.320	mm
Bare cable width H.F./L.F.	13.2/13.3	mm
Cu/non-Cu ratio H.F./L.F.	0.85/2.15	
Operating current	11180	A
Operating point on load line (both cond.)	86%	
Copper current dens. H.F./L.F.	1.16/1.14	kA/mm^2
Magnetic stored energy (2 apert.)	2.6	MJ/m
Inductance at high field (2 apert.)	40	mH/m
Turn number H.F./L.F. (1 apert.-1 quadr.)	33/68	35/80

This design requires for the entire collider ring a total conductor mass of 7590 tons (3100 tons for the high field conductor and 4490 tons for the low field conductor). The calculations have been performed considering the optimized 2D dipole area (133.2 cm^2 for a double aperture), 4578 dipole units, length of 14.3 m per dipole and conductor average density of 8700 kg/m3.

The mechanical structure chosen for the magnet is based on the bladders and keys ("B&K") technology, with some modifications. B&K is a new approach used for example for the assembly of HL-LHC and LARP quadrupole magnets. It has never been adopted to design cosθ dipoles. As agreed by the EuroCirCol consortium, the mechanical design has been performed for a single aperture magnet. This is partly related to complexity of the design, which suggests advancing step by step, and partly due to the fact that the EuroCirCol prototype will be a single aperture magnet. Due to the large magnetic forces arising when charging the dipole up to 16 T, a standard B&K mechanical structure is cannot fulfil all mechanical requirements. It is fundamental to preserve the pole-coil contact when the magnet is fully energized and, at the same time, to keep the stresses within the given limits. For the conductor, the stress limit is 150 MPa at room temperature and 200 MPa at cryogenic operation temperature. A promising configuration is shown in Figure 8.
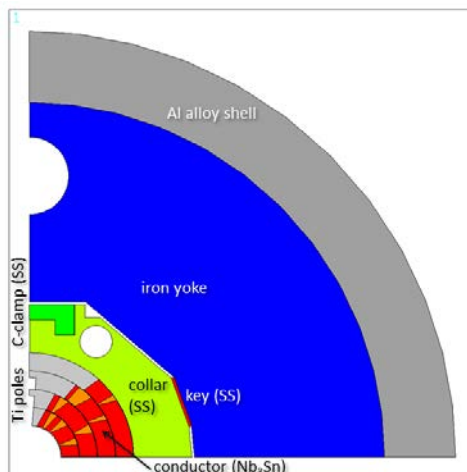

Figure 8: One fourth of the cosine-theta mechanical structure.

4.3. COMMON-COILS

To perform an efficient parametric optimization of common coil configurations, a custom tool based on a spreadsheet has been developed. This provides first estimate of the hotspot temperature in each coil block, taking into account a given field distribution. Electromagnetic calculations have been made using Roxie. In the design, only double pancake coils have been used, since they are more compact. Single layer coils require additional space in the cross section for the current leads. As the driving cost of the magnet fabrication is the amount of superconducting cable, the objective of the optimization has been to reduce the coil volume. This imposes the use of ancillary coils around the aperture, which complicates the magnet fabrication, but allows reducing the spacers placed at the region where cables are more efficient. More than 10 different design variants have been parametrically studied to achieve efficient use of the conductor, resulting in a design (Figure 9) which has a potential to compete with the common coil and the cosine-theta in terms of conductor use.
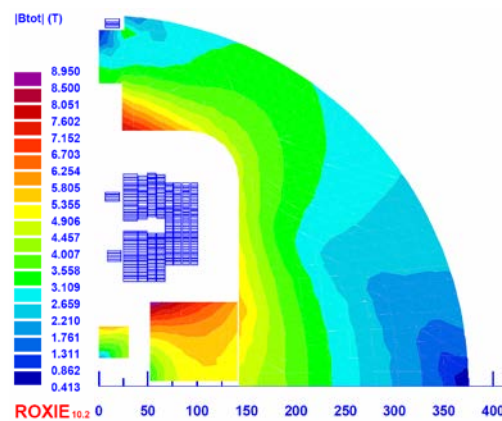

Figure 9: One fourth of the common-coil magnet cross section.

5. NEXT STEPS

In addition to the continued development of the tools (quench analysis and cost model), the next steps focus on two objectives:

1. Establish a reference design option for the conceptual design report deliverable. The study will include quench protection (magnet and circuit) and cost estimate;

2. Perform the construction design of a single aperture short model, using the same specification as the reference design (in particular aperture, field quality, margin).

A 2nd review of EuroCirCol WP5 will take place in mid 2017, with the main scope of providing feedback about the evolution of the reference design option.

6. CONCLUSIONS

The activities performed to produce the first deliverable "overview of magnet design options" consisted in setting up the tools to perform and support the design work, in exploring different design options, and in keeping a continuous contact in an iterative process between the different parties engaged in this collaboration. This aspect of the work is considered to be extremely important and was a key for the successful scientific result of the activity. The homogeneity of the different studies, and the high quality of the scientific work is the result of a remarkably effective attitude of all parts in sharing information through different channels: regular video-meetings (more than one per month in average) in addition to several meetings in person and a large amount of mail exchanges and telephone discussions, an external review, the attendance to workshops and conferences. In particular during the reference period all tasks of WP5 were represented at the EuroCirCol annual meeting (see http://indico.cern.ch/event/448415), the FCC week (see http://indico.cern.ch/event/438866), the ASC conference (see http://ascinc.org).

For each option, two different stages have been considered (18% and 14% conductor load-line margin). This choice has opened new directions of coil cross section optimisation, in particular:

1) efficient use of the high field **conductor**, which **can be operated at a higher current density**

2) considerable **decrease of the conductor amount**

3) considerable **reduction of the magnet inductance** thanks to more compact coils and higher current

The coil cross-sections of the three designs are depicted in Figure 10, both for 18% and 14% margin. The overview of the magnet design option is now complete and the work to finalize and compare these options for the production of the next deliverable D5.2 (identification of preferred dipole design options and cost estimates) has started.
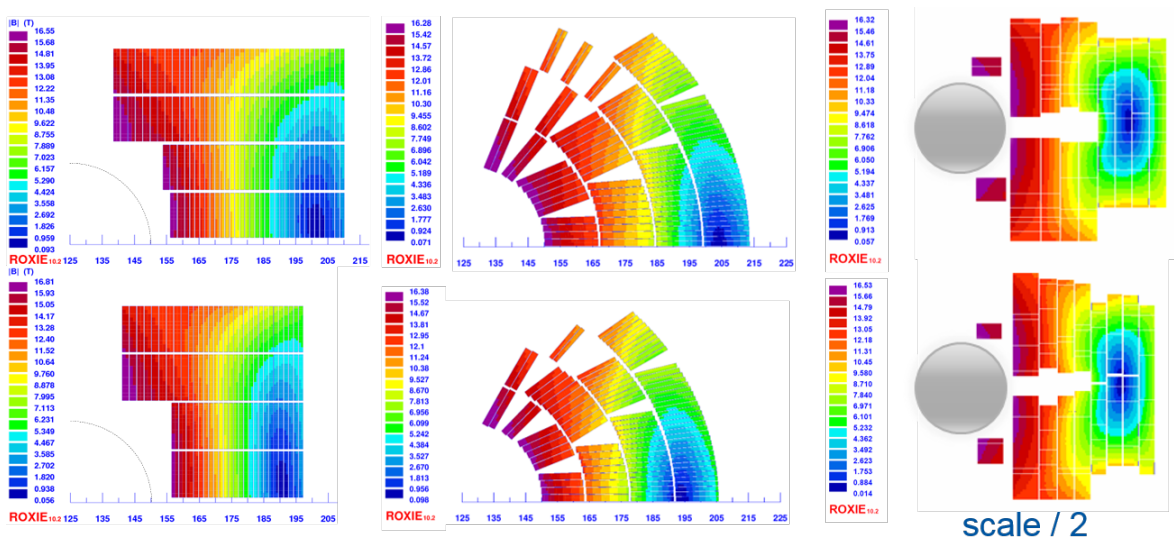

Figure 10: Overview of the coil cross sections for the three design variants
(from left to right: block-coils, cosine-theta and common-coils). Top is the 18% margin version, bottom the 14% margin.

7. REFERENCES

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8.   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