I.FAST

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MILESTONE REPORT

CONCEPTUAL DESIGN OF HTS MAGNET

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ABSTRACT

This conceptual design report presents two electromagnetic designs of the HTS Canted Cosine Theta (CCT) magnet option. We highlighted the complexity of the protection and proposed a compact design based on the resistive insulation technology (“MI like”) and an insulated version with added copper stabilizer. Both option are generating 4 T of dipole field without Iron shell and with at least 10 K of margin at an operational temperature of 10 K. We decided to consider a simple cable based on a co-winding of commercial REBCO tapes in order to respect the time scale of the project and the conductor budget. Electromagnetic and protection studies are presented in this report and the further required studies are discussed at the end of the report.

For more information on IFAST, its partners and contributors please see https://ifast-project.eu/

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	Name	Partner	Date
Authored by	T. Lécrevisse	CEA	31/05/2022
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Executive summary

An objective of IFAST WP8 is to develop a technology of Canted Cosine Theta (CCT) magnet built of High Temperature Superconductor (HTS) material. A first step to fulfil this objective is the electromagnetic design based on the requirements for such magnet and the considering the particularity of HTS materials. A first simplified protection study is also included in this conceptual design in order to propose two practical solutions: an innovative "MI like" design and a more classical insulated version. Both are discussed in this report.

In order to stay in the timeline of WP8 and Task 8.3, we chose an easily available conductor and found the best way to use it. The overall current density in commercial REBCO tapes (above 2-kA/mm² at 15-K and 5-T perpendicular to the broad face) and the wide range of suppliers make it a good candidate for such application even if magnetization will have to be evaluate.

The future plan is to develop the winding way and the leads parts allowing the current connections between cables and layers and adjust the designs for the engineering design. We also will add an adapted iron shell to reduce du fringe field and improve the margins / lower the conductor volume..

1 Introduction

The WP8 “Innovative superconducting magnets” includes a prototyping activity that aims at achieving a breakthrough in the technology of SC Canted Cosine Theta (CCT) magnets. The main technical goals are to: a) reach 4-6 T operative field in a 60-90 mm free bore with moderate-fast ramping rate of 0.1-1 T/s; b) design and test an integrated dipole/quadrupole (or even multipole) coil winding, which would allow a powerful achromatic transport of the beam; c) design and test the combined function CCT configuration to use the CCT as main magnet for a synchrotron or beam lines; d) design and test a straight CCT dipole using HTS material.

The present work is part of the preliminary study of the HTS CCT aiming to propose a design and evaluate the main developments required to build such magnet. We are focusing on the electromagnetic design and the protection aspects in this report, which is the baseline to the future developments.

2 I-FAST HTS CCT main parameters

The baseline of our CCT demonstrator will mainly follow the same parameters that its LTS counterpart but with some modifications to take into account HTS particularities. As the plan is to use REBCO 2nd Generation HTS material, we will only look at a straight configuration, which is already challenging.

The question of design margin for HTS magnet is quite different that from LTS magnet. In this study, we agreed to evaluate a solution with a minimal thermal margin above 10-K to take into account the expected high AC losses due to the HTS material. We also are looking at a solution ideally at an operating temperature of 10-K as optimized cryocooler are commercially available. Also at the targeted magnet field of about 4-T in the worth direction (perpendicular to the tape).

The following table is summarizing the HTS CCT key parameters.

Table 1 : HTS CCT key parameters

Parameters	Values	unit	Comments
Magnet type	**CCT**	-	
Geometry	**Straight**	-	
Central magnetic field B_0	**4**	T	as HITRI+ and SIGRUM demostrators No specific field quality at this stage
Nominal current	**< 2**	kA	it limits the choice for the conductor/cable
Magnetic and physical length	**0.8, 1**	m	
Bore diameter	**80**	mm	as HITRI+ and SIGRUM demostrators
dB/dt	**0.4**	T/s	as HITRI+ and SIGRUM demostrators
Operation temperature	**10**	K	10-K optimized cryoccoler Lower temperature depending on margins
Temperature margin at 10 K	> 10	K	High temperature margins due to high expected AC losses
Superconductor	ReBCO	-	Low AC losses cable to be defined

3 Electromagnetic design and protection study

3.1 Electromagnetic design

The objective of this study is to evaluate a possible conductor path to reach the targeted parameters using REBCO materials. In order to perform the study, the RAT-GUI software from Little Beast Engineering was used [1]. At this stage, we conserved a rectangular cross section in accordance with the REBCO tape shape. A major issue with this material is the high dimensional ratio (width and thickness) which is not allowing any hardway bending. We decided to consider a Frenet-Serret path, which is avoiding any hardway of the cable with a rectangular section.

After a first electromagnetic design option, we evaluated the protection aspect in order to adjust the Copper/Sc ratio to optimize it for an insulated version. The protection of HTS magnet is a challenging question, which require dedicated 3D models for a CCT. Such models are not available in the consortium and we focused on the adiabatic hot spot criteria for this preliminary approach.

3.1.1 Cable option

We are looking to an available cable solution with reasonable supplying delay and cost. Also for cryogenics and power convertor cost, a relatively low current powering is required: we have to stay below 2-kA in our study. This constrain is limiting the type of cable to a 1 to 3 tapes cable (other are for high current powering).

From those constrains, the first approach is to consider a multi tape stack based on single commercial tape with an assembly during the winding: the consortium has not the tooling to preassemble a multi-tapes stack cable in several tens of meter pieces. In addition, the chosen width is 4-mm, which is a quite common REBCO tape width (easily available) allowing a reasonable powering current in a cable and limiting the AC losses compared to wider tapes. The cable options are presented in *figure 1*, with (right) and without (left) added copper stabilizer layers. The elementary tapes is considering being 66-µm thick which includes 40-µm Hastelloy substrate and 10-µm surrounding copper layer. The 6-µm thickness left are for all other layers (Buffer layers, HTS and silver). The models will be adjusted to the real tape dimension after order (might deviate up to 10-µm).

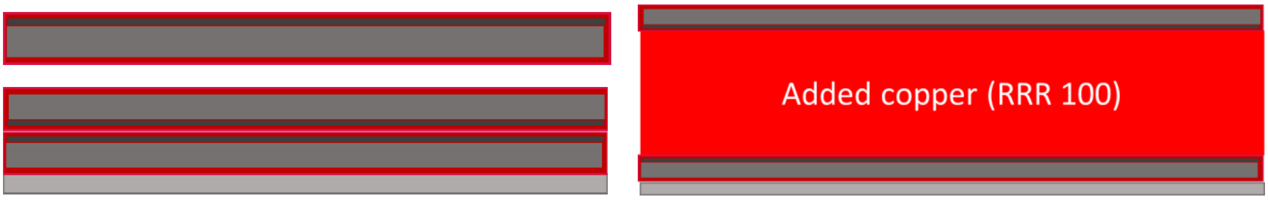

Figure 1: Elementary tape (top left), cable with (right) and without (bottom left) added copper stabilizing layer. Black line is for HTS layer, red parts are copper and dark grey is for Hastelloy® substrate layer. Light grey is for the cable-to-cable "insulation".

From this elementary tapes and cables, we consider a multi-cable stack inside a groove as presented in *Figure 2*.

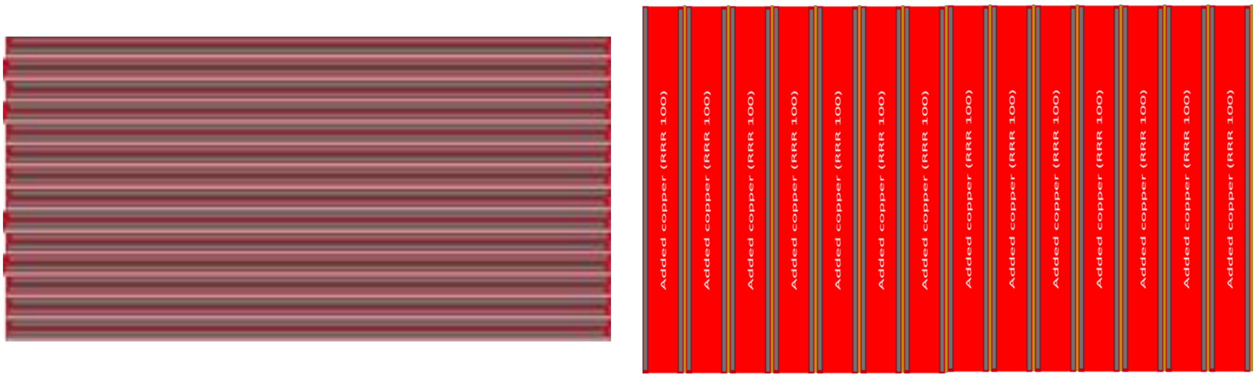

Figure 2 : 14 cable stack with added copper stabilizer (right) and without (left)

Both stack configurations have been evaluated in the electromagnetic design options.

3.1.2 Preliminary electromagnetic designs

Designing a CCT shape HTS magnet is not an easy work considering classical COMSOL or OPERA softwares. A first difficulty is to create a conductor path without hardway bending. In order find a suitable conductor path and evaluate the margins, we used the RAT-GUI (Little Beast Engineering) which has a Frenet-Serret path option leading to a design without hardway bending. Reaching a dipole field of 4-T won't be an issue thanks to the high performance of HTS conductors, even at 10-K with relatively low field (i.e. below 10-T). Nevertheless, HTS REBCO materials are not available in multi filamentary cables but are supplied like thin and wide tapes, leading to high screening current and related AC-losses. For this reason, we will look at a design with high temperature margins (about 10-K) in order to avoid a quench due to the AC-losses and related local temperature increase.

3.1.2.1 Electromagnetic design without added stabilizer

In a first approach, we decided to limit the design study at a two layer CCT to lower the complexity of the assembly. The conductor path of the first design option with the parameters in *Table 2* is presented in *Figure 3*. This option is considering a cable rectangular section, 4-mm wide with the thickness (deep of the groove) adjusted to reach the targeted field with sufficient operational margins.

The margins is a challenging aspect of the study. Indeed, it will highly depend on the critical surface model (depending on three parameters for REBCO materials: the temperature, the magnetic induction and its orientation with the HTS layer plane). We consider an available model for one supplier. It will have to be updated to what we will order in the second project phase.

Table 2 : RAT-GUI CCT cables path parameters

Geometrical parameters			
Parameter	Unit	Value	Remarks
Layer / turns per layer	-	2 / 85	
Cables per groove	-	18	
Inner radius	mm	44	free aperture of 80 mm
Amplitude / pitch angle	mm / degree	76.2 / 30	optimized angle from [2]
Winding pitch	mm	5	
Distance between layers	mm	8	
Path rectangular section	mm x mm	4 x 2.9	
Frame length	m	36.3 (L1) / 39.3 (L2)	two layers L1 (inner) and L2 (outer)
Total length (cable/tape)	m	1493 / 2986	comprising 10 % over length
Operational parameters			
Overall current density	A/mm²	1698	
Groove current	A	19800	
Dipole Field B_0	T	4.0	without Iron

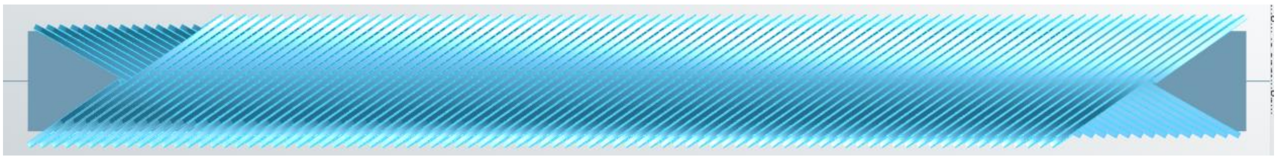

Figure 3 : 2 layer CCT of 85 Turns considering Frenet-Serret path without hardway bending (without leads included)

To stay below the powering current of 2-kA, the 2.9-mm thick HTS path will be filled with 18 dual tapes cables (like presented in bottom left scheme in *Figure 1*). Each cable will be made of two HTS tapes (face-to-face to improve the current sharing), 56-µm to 66-µm thick and an insulation (or metallic) layer of 20-µm to 30-µm thickness. Considering this parameter the nominal current will be close to 1100-A. Each cable will be connected from inner layer to outer layer and outer to inner layer at both ends of the magnet following the simplified scheme in *figure 4* where L1 and L2 are for inner and outer layer respectively and C_i the i-cable in the groove. A dedicated connection technology will have to be developed in order to connect inner cables to outer cable two by two. A scheme of the layer-to-layer cables series connection is presented in *Figure 4* bottom for five cables. The red line and arrow are representing the current direction (coming from Layer 1, cable 1 and going out from Layer 2, Cable 5).

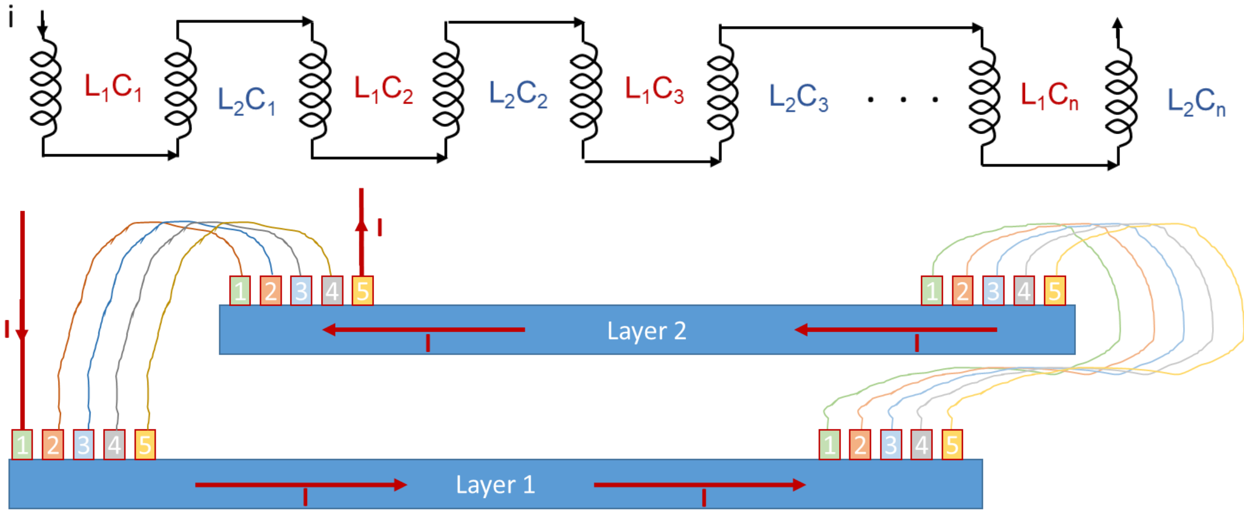

Figure 4 : Proposed electrical connection between layers and cables (top) and scheme of principle for 5 cables (bottom)

We summarized the electromagnetic parameters in *table 3*.

Table 3 : Electromagnetic parameters

Parameter	Unit	Value
Inductance	mH	117.9
Stored Energy	kJ	71.0
Cable current	A	1100
Groove current density	A/mm²	1698
B_0	T	4

The two major developments on such magnet will be the connections between cables (dual tapes cables) and the former/winding/impregnation. Nevertheless from an electromagnetic point of view, we can estimate the margins considering the field components, the temperature and tape manufacturer. Some fits have been recently added inside GUI-RAT software and we choose the Shanghaï Superconductor Technology (SST) fit from Robinson institute [3], which is the most recent one. Comparison between suppliers from this reference is presented in *Table 4*. The margin estimation from our model are in good agreement with the values in *table 4*. Though we do not know if the measurements were made on common of high performance tapes (each length have a different performances), we are keeping this reference for our study. We are presenting the magnetic field component at nominal field and the margin estimation in *figure 5* and *figure 6*, respectively

Table 4 : HTS tapes performances for different suppliers measured at Robinson Institute [3]

Robinson Institute Reference (year)	**I_c/w at 15 K, 5 T perp. [A/cm]**	**I_c 4 mm at 15 K, 5 T perp. [A]**	**j_e tape (4 mm wide, 66 µm thick) at 15 K, 5 T perp. [A/mm²]**
SST High Field, Low temperature 2G HTS (21/02/2022)	1646	659	2494
Fujikura FYSC 2G HTS (29/10/2021)	1538	615	2330
SuperPower Advanced Pinning 2G HTS (02/03/2021)	1444	578	2188
SuperOx YBCO 2G HTS 05/02/2021)	1593	637	2414

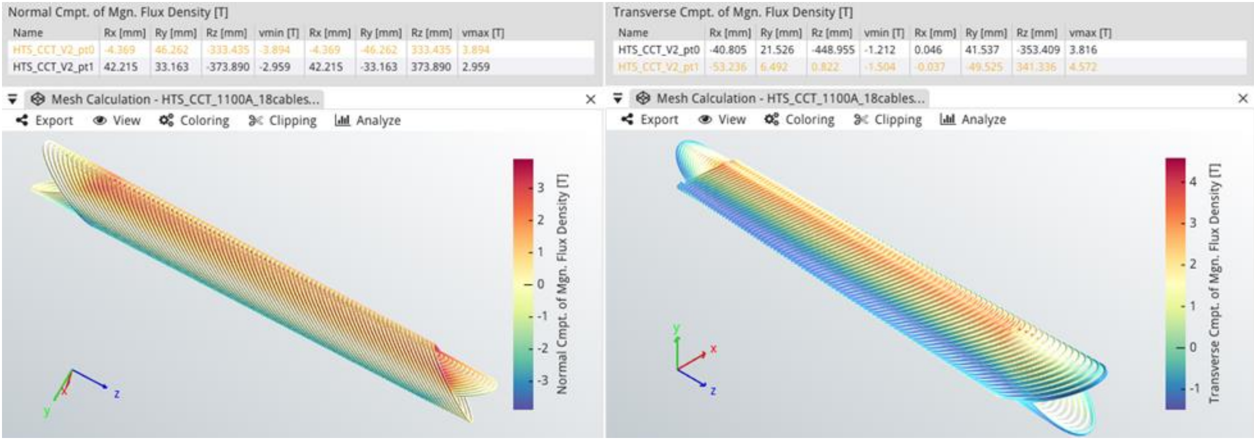

Figure 5 : Normal (left) and parallel (right) components of the magnetic flux at nominal current

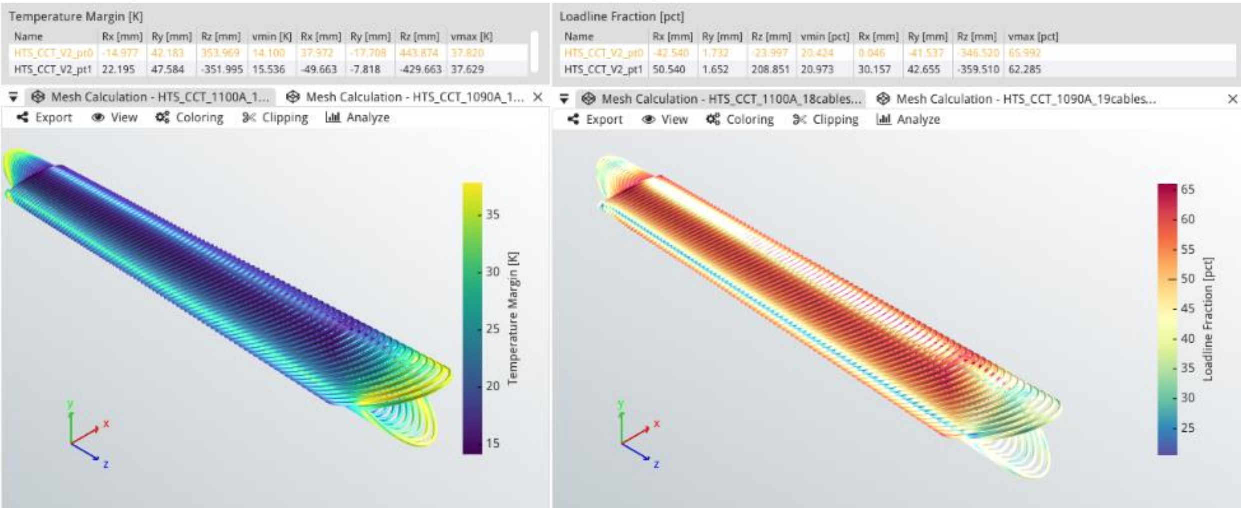

Figure 6 : Percentage on the Loadline (left) and Temperature margin (right) at 10 K and I_{nom}

The proposed design reaches a temperature margin of 14.1 K, giving more margins that required. Considering this preliminary study and the design parameters which will have to be confirmed by practical trials, we considered that this design is suitable for the project and we will adjust it after other studies (the possibility to add iron shell is still ongoing). Roughly, the 14.1 K margin gives an enthalpy margin of about 720 µJ/mm^3, which is two order of magnitude higher that classical LTS magnets.

3.1.2.2 Protection aspects

The protection of HTS magnet is a major issue to their use in reliable machines since many years. It is a reason why many groups worldwide are working on it and why new winding approaches have been studied since about 12 years. The high temperature/enthalpy margin discussed previously lead to a very low quench velocity and therefore a very local heat dissipation. Such local phenomena often leads to local burnt or damage of the winding. Typically, the quench velocity in HTS magnet is two to three order of magnitude slower that its LTS counterpart.

If some quench models have been developed for solenoids HTS magnets, we have no available tools to do it for CCT magnets. We consider in the following parts three different cases: the peak temperature due to the discharge, the peak temperature due to the discharge with fixed detection/activation delay and finally the peak temperature including an estimation of the delay to detect a certain voltage threshold.

3.1.2.2.1 Adiabatic hotspot criteria during discharge

In this study, we are looking at the maximum temperature reached due to the heat dissipation inside the magnet during the discharge. T_{max} is obtained following the *equation (1)* where we are considering a cable composed of Hastelloy and Copper.

$$\int_{T_{op}}^{T_{max}} \frac{C_{v,av}(T)}{\rho_{metal}(T)} dT = \int_{0}^{t_f} j_e^2(t)\, dt \qquad (1)$$

Where T_{op} and T_{max} are the operational temperature (10 K in our study) and the maximum (peak) temperature respectively; $C_{v,av}(T)$ is the volumetric heat capacity of the cable / winding (average), depending on the temperature; $\rho_{metal}(T)$ is the resistivity of the metal matrix; $j_e(t)$ is the overall current density in the cable, depending on the time; and t_f is the final time when the magnet is discharged.

The study is considering the two cables options presented in *Figure 1*: the simplest cable with only two HTS tapes without added copper and a second cable with added copper layer.

For the protection scheme of this study, we consider the discharge of our magnet (inductance L_{CCT}) in a dump resistor R_d (equivalent of an RL discharge). R_d value is determined by considering a maximum discharge voltage U_d. We choose arbitrary $U_d = 500\,V$ as an acceptable discharge voltage. The study parameters are presented in *Table 5*.

The result of this study is presented in *Figure 7*. The curve represent the maximum hotspot temperature (T_{max}) in regards to the added copper thickness in the cable. It considers only the heating during the magnet discharge inside the dump resistor. Below 100 µm of added copper, the temperature is going above 500 K but it is out of range of the materials thermal parameters.

In order to have a chance of protecting the magnet, the hotspot temperature should stay below 300-350 K including the detection time. It means that the cable will require at least 150 µm of added copper (300 K) and even more to take into account the warming up during the detection, which is the purpose of the next study.

Table 5 : First protection study parameters

Parameters	Unit	Value	Comments	Reference
HTS tape Copper thickness	µm	46	RRR of 15 under 5 T	Cryocomp software
Hastelloy thickness	µm	80	-	https://aip.scitation.org/doi/10.1063/1.2899058
Added Copper thickness	µm		RRR of 100 under 5 T	Cryocomp software
T_{op}	K	10		
I_{op}	A	1100		
R_d	mΩ	455		
L_{CCT}	mH	117.9		

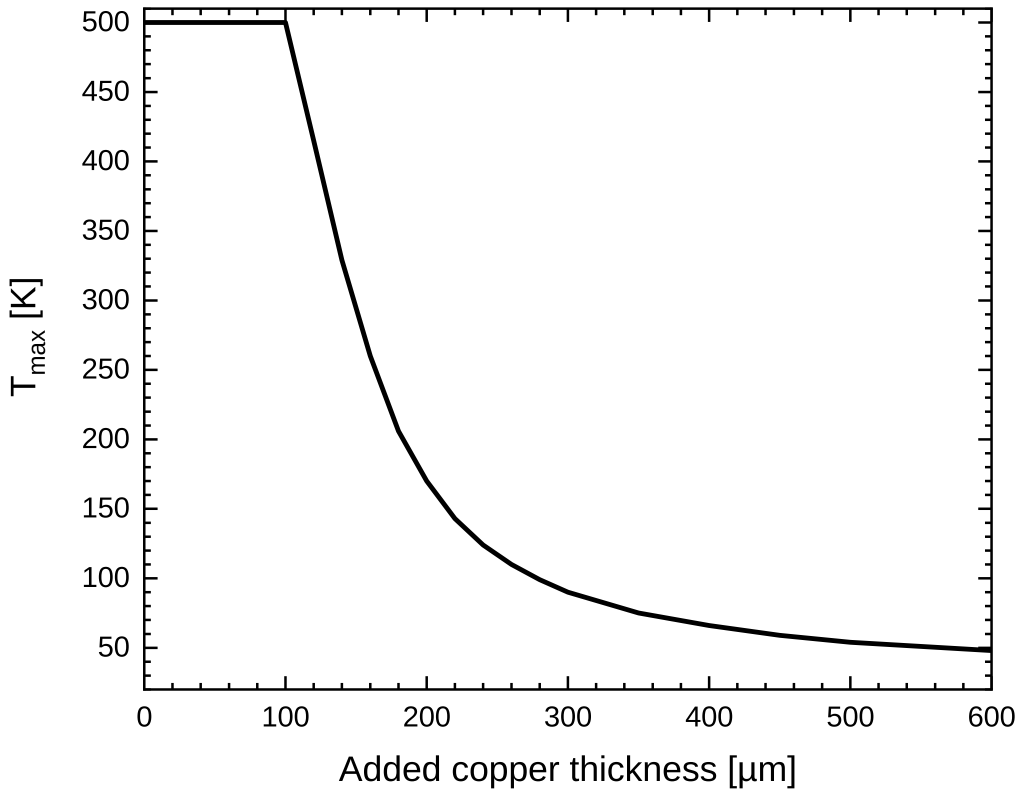

Figure 7 : T_{max} due to the the discharge depending on added copper thickness

3.1.2.2.2 Adiabatic hotspot criteria including the detection time

The previous study consider only the warming up during the discharge. In this part, we add the warming up during the detection and the discharge activation. In order to do so, the right part of equation (1) can be updated as follow:

$$\int_0^{t_f} j_e^2(t)\,dt = j_0^2 * t_{det} + \int_{t_{det}}^{\infty} j_e^2(t)\,dt \qquad (2)$$

Where j_0 is the operational current density (constant); t_{det} is the detection time (include the protection activation); and $j_e(t)$ is the current density during the discharge (like previous study). The results are presented in *Figure 8* for time detection between 0-ms and 100-ms and added copper thickness from 0-µm to 600-µm. Three temperatures ranges are defined: safe range below 200-K, risky between 200-K and 300-K and highly risky above. In order to stay in the safe range with a reasonable, but still very challenging for HTS, detection time (> 60-ms), an added copper thickness above 270-µm is require.

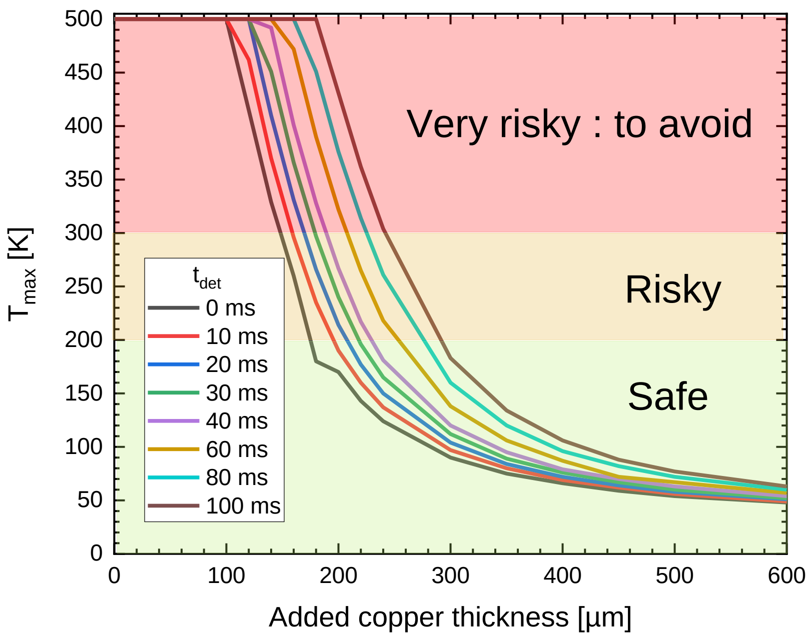

Figure 8 : T_{max} depending on added copper thickness and detection time

As said *supra*, the detection time of 60-ms is still challenging for HTS material. This is because of the very slow quench propagation inside HTS cables because of the very high thermal stability. We will look at this aspect in the next part in order to evaluate if the proposed 60-ms is a reasonable detection time.

3.1.2.2.3 Quench detection effect on hotspot temperature

The quench detection in HTS magnets is a very challenging aspect. Indeed, a classical way to do it (for LTS magnets) is to measure a resistive voltage during a few tens of milliseconds in order to consider that the quench is occurring in the magnet. If it is quite efficient in LTS magnets where the quench velocity is very high (several to several tens of m/s), it is less obvious for HTS magnet for which the quench velocity is two to three order of magnitude lower (several to several tens of mm/s) [4-5].

We propose here to evaluate the detection time depending on the quench propagation and the voltage threshold. We consider the material properties at 90-K in this study, even if the quench temperature in HTS magnet is spread between T_{cs} (current sharing temperatures) and T_c (critical temperature), depending on the magnetic induction value, angle (both) and the current density (T_{cs}). This temperature range might be of several tens of Kelvins.

We presents the study results in *Figure 9*. We looked at the maximum temperature depending on the added copper thickness (0-µm to 520-µm) and threshold (from 0.1-mV to 100-mV) for two quench velocity value (1-cm/s and 10-cm/s). In this study we added a 10-ms delay for signal integration and contactor opening. In the red area, it is impossible to stay below 300-K. In the orange area it is risky (200-K to 300-K) and the green area is the safe condition below 200-K. As explained before, a quench velocity of 10-cm/s is very high for HTS material. The value of 1-cm/s is more reasonable. In order to have a protectable magnet with this study, we can estimate some couple (added copper thickness / U_{det}) to have a protectable magnet. Values are summarized in *table 6*. For now, the question is what reasonable voltage can be measured in a noisy environment. In a conservative way, a voltage below 5-mV has to be measured (in about 13-V of inductive voltage to reach a $\frac{dB}{dt} = 0.4\ T/s$).

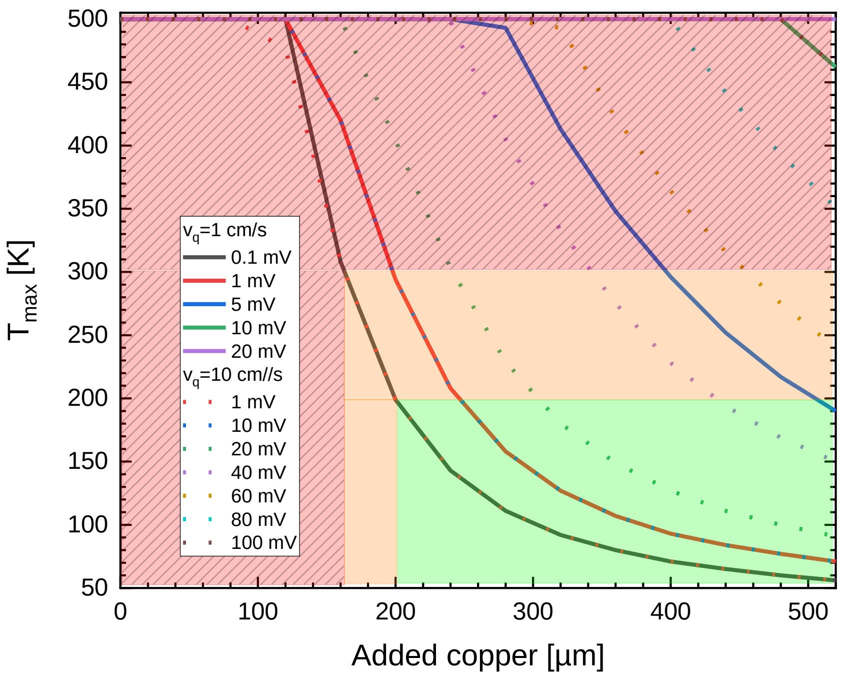

Figure 9 : Maximum hotspot temperature depending on copper thickness and detection threshold for $v_q = 1\ cm/s$ and $v_q = 10\ cm/s$ (incl. 10 ms delay for activation)

Table 6 : Minimum added copper requirement for protection

cases	$v_q\ [cm/s]$	$U_{det}\ [mV]$	Minimum added copper [µm]
1	1	0.1	200
2	1	1	280
3	1	5	520
4	10	1	200
5	10	10	280
6	10	20	320
7	10	40	440

3.1.2.2.4 Conclusion on the HTS CCT protection

With the preliminary protection study presented previously, the protection of our CCT is a very challenging aspect and would require a dedicated numerical models (a 3D electromagnetic model allowing to evaluate the quench behaviour in the magnet) which is not available at this time. The simplest hotspot adiabatic model shown that it is really complex to protect the magnet considering a classical detect (by voltage) and dump protection scheme. The main issue is related to the quench detection in a noisy environment. A very low voltage (lower than 5-mV) has to be detected with only 10-ms delay (integration of signal to avoid false detection and opening of a contactor). A solution of adding 280-µm of copper (for an initial cable thickness of 132-µm).

Effort has to be made to evaluate the less risky CCT and cable design solution. It is the purpose of the following part

3.1.2.2.5 Quench risk mitigation

In order to lower the risk of damaging the magnet during a quench, we evaluate a few option in *table 7*. The option are considering the magnet itself (cable, margins, winding technology) and the detection possibilities.

Table 7 : Options to mitigate the risk in case of a quench

Change / technology	Benefits	Drawbacks	Comments
Considering a "MI like" winding	Reduce drastically the thermal damage risk	- Add radial currents (field quality and dissipations) - Transient models complexity	Self-protection behaviour never tested in CCT configuration.
Adding 280 µm copper for an insulated magnet	- Lower risk of damage - Known field - Easiest modelling	- Require more accurate models - Winding/connections complexity - About 3 time thicker cable	The CCT former and winding feasibility has to be check (rectangular shape 4 mm x~8 mm grooves)
Add more cables/HTS core	- Increase the thermal margin (avoid quench)	- Lower voltage - Higher HTS cost - Electrical connection more complex	Solution to avoid a quench but complex to evaluate with AC losses
Detection with optical fibre	- Avoid low voltage measurements - Localisation of the transition	High AC losses heating during magnet transient leading to risk of false detection	We have no experience on such detection way
Detection of current redistribution in the cables	- Pre-quench detection	Require maybe more than 2 HTS tapes in a cable (complexity)	Feedback from experiment on Roebel cable but never really used

3.1.2.3 "MI like" design option

3.1.2.3.1 Principle

The "MI" technology [6] is based on the well know No-Insulation (NI) technology. In such winding, the insulation material is replaced by a resistive material (like Stainless steel). In case of a local transition occurs, the current automatically bypass the resistive are through the turn-to-turn resistance and avoid its overheating.

3.1.2.3.2 Background

CEA firstly used the MI technology for UHF magnet in the CEA/CNRS French HTS insert NOUGAT in 2018. This technology was chosen to have a protectable, very compact insert to reach 10-T in a 20-T background magnetic field. The numerical simulation made on pancakes solenoids in the past years shown that it is a close to self-protected magnet even at very high current density. It has been confirmed by experiments on NOUGAT insert since 2018 with several quenches with current density above 700 A/mm² and magnetic field up to 32.5-T. The main drawback of this technology is the turn-to-turn finite resistance, which induces radial currents during transient behaviour and the related heat dissipation and magnetic field quality losses. The use of high resistance materials like stainless steel is helping to limit the bypassing current and that is might be useful for this project.

3.1.2.3.3 Implication in the electromagnetic design

This solution is compatible with the previous design, which included a 30-µm insulation layer between cables. In order to implement the "MI" technology, we have to insert a 30-µm metallic tape between the cables inside a groove. A groove will therefore contain 18 cables (made of two REBCO tapes face-to-face) with a 30 µm-thick metallic tape between each cable.

3.1.2.3.4 Losses evaluation

If it is not possible to evaluate the AC losses and the radial current losses (and effect on the field quality) for HTS CCT for now, we performed a study on a small four pancakes solenoid (small because of the computation time). Even if it has to be confirmed with more accurate models, the first results are encouraging. We present the AC losses and radial current losses in *Figure 10*. The pancake model is consisting on four pancakes made of 200 turns. Each turn consists in a 6-mm wide REBCO tape co-wound with a Stainless steel tape. The turn-to-turn contact resistivity is set at 10 mΩ.cm². The magnet inductance is 40.6 mH and the magnetic constant is 13.16 mT/A

The technology, and mainly the processes to obtained a custom resistance, is still under developments but preliminary simulation results made on a small four pancake solenoid geometry (no CCT model are available for such technology) shown that radial currents might not be the first source of heat dissipation in an REBCO HTS magnet. The simulation results are presented in *figure 10*.

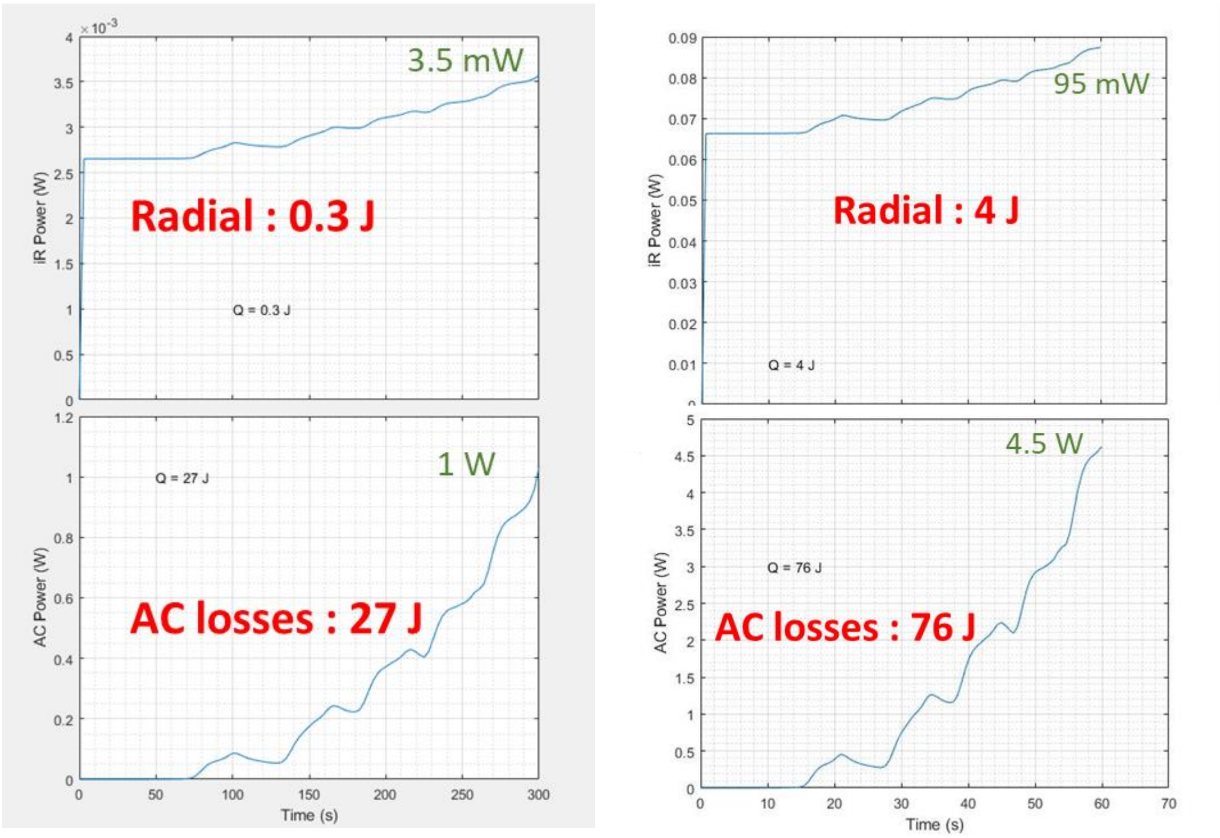

Figure 10: AC losses and radial current losses (iR) during a four pancake magnet charging (at 1 A/s -13.2 mT/s- (left) and 5 A/s- 65.8 mT/s- (right)).

The AC losses and radial current losses will have to be evaluated for the final study (including the good cable section) of this design. It is not included in this report due to the leak of time and resources.

3.1.2.3.5 Preliminary conclusion on "MI" CTT

From these preliminary results, this technology might be an interesting way to develop the HTS CCT technology with a lower risk of magnet damages during the tests. It will allow us to focus on the critical developments (former, winding, assembly, electrical connections…).

3.1.2.4 Insulated magnet with added copper stabilizer

In order to consider an insulated version of the magnet, we will have to add 280-µm of copper in each cable. It leads to a slightly different electromagnetic design, which is summarized in *tables 8 and 9*. The grooves deep is increasing by a factor close to three, which might increase the former complexity. It allow a much lower overall current density and a tinny increase of the current compared to the previous design ("MI like").

Inductance and magnetic energy are also slightly increasing. Nevertheless the change is small on the design margins and can be managed and adjust when choosing the tape performance for the magnet. To be conservative we proposed 19 cables instead of 18 in this design.

Updated conductor path is presented in *Figure 11*, magnetic flux components in *Figure 12*, loadline and temperature margins in *Figure 13* and magnet axis magnetic flux components profiles in *Figure 14*.

Table 8 : RAT-GUI insulated CCT parameters

Geometrical parameters			
Parameter	Unit	Value	Remarks
Layer / turns per layer	-	2 / 88	
Cables per groove	-	19	
Inner radius	mm	46	Free aperture of 80 mm
Amplitude	mm	76.2	
Winding pitch	mm	5	
Distance between layers	mm	12	
Path rectangular section	mm x mm	4 x 8.4	
Frame length	m	38.3 (L1) / 43.2 (L2)	two layers L1 (inner) and L2 (outer)
Total length (cable/tape)	m	1700 / 3400	comprising 10 % over length

Operational parameters			
Overall current density	A/mm²	618	
Groove current	A	20762	
Dipole Field B_0	T	4	

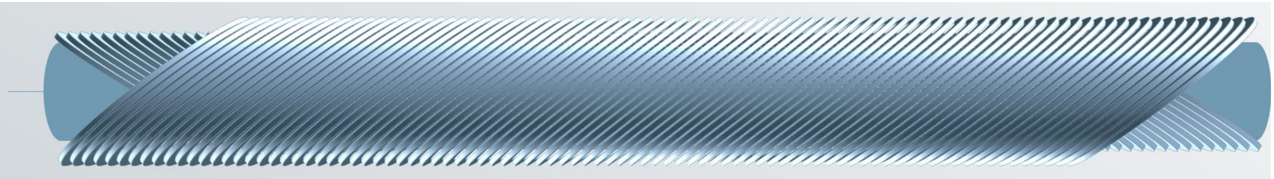

Figure 11 : 2 layers insulated CCT of 88 Turns considering Frenet-Serret path without hardway bending

Table 9 : Electromagnetic parameters

Parameter	**Unit**	**Value**
Inductance	mH	139.8
Stored Energy	kJ	82.9
Cable current	A	1090
Groove current density	A/mm²	618
B_0	T	4

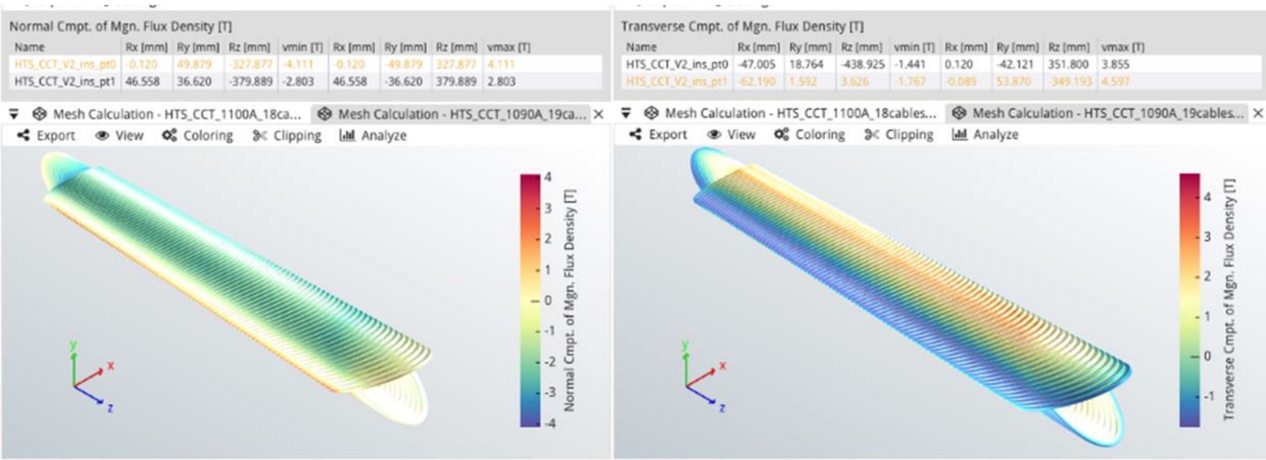

Figure 12 : Normal (left) and parallel (right) components of the magnetic flux at nominal current

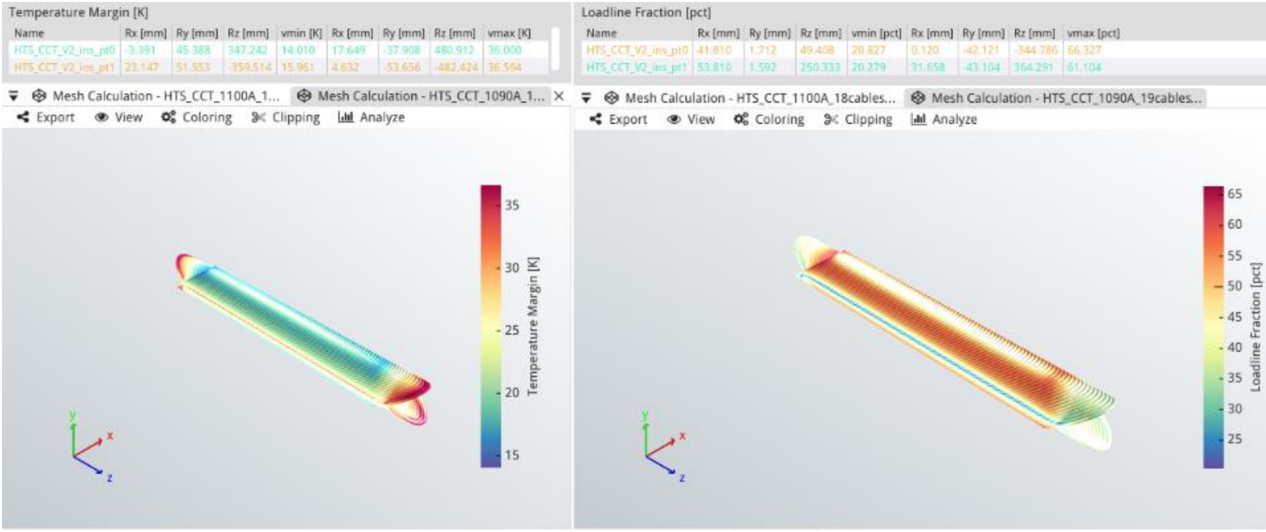

Figure 13: percentage on the loadline (left) and Temperature margin (right) at 10 K and I_{nom}

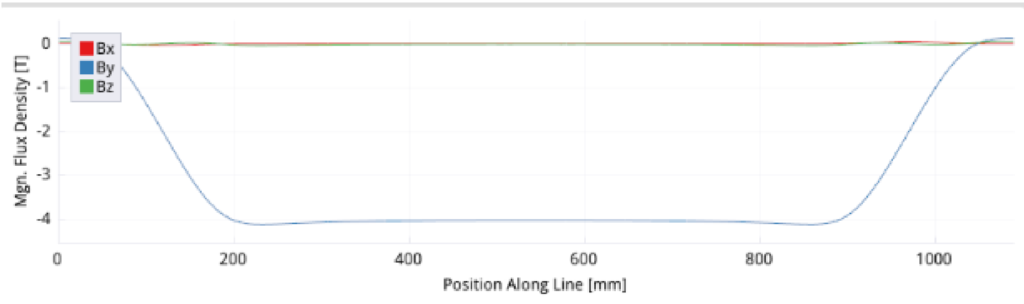

Figure 14: Magnetic Induction on CCT axis

The AC losses of the conductor and/or magnet will have to be evaluated as for the "MI like" design. This study will have impact on the margins estimation and cryogenics design as a quench will stay quite risky for this solution.

3.1.2.5 Electromagnetic "MI like" and Insulated designs summary and comparison

The main electromagnetic parameters of the two proposed design are summarized in *Table 10*.

Table 10 : designs main parameters comparison

Parameter	Unit	"MI like"	Insulated
Inductance	mH	117.9	139.8
Stored Energy	kJ	71.0	82.9
Cable current	A	1100	1090
Groove current density	A/mm²	1698	618
B_0	T	4	
Turns per layer	-	85	88
Cable per groove	-	18	19
Cable path section	mm x mm	4 x 2.9	4 x 8.4
Inner Diameter (winding)	mm	44	46
Omega (Winding Pitch)	mm	5	
Amplitude / pitch angle	mm	76.2 / 30	
Distance between layers	mm	8	12

3.2 Option of adding Iron shell

A way to increase the margins in our HTS design is to add an iron shell to lower the operating current and shield the fringe field. We estimated that about 1 T might be generated by the Iron sheel which might lower the HTS requirements by about one third. The 30 Gauss and 5 Gauss lines are presented in *Figure 11* for the two main CCT plans up to 2.5 m from the magnet centre for the "MI like" design. The 5-Gauss line is closed to 2-m in the (xz) plan and 2.5-m in the (yz) plan. In order to stay in the 2 meters limit, the magnet will have to be shielded and it will also help for lowering the current density and increasing the design margins.

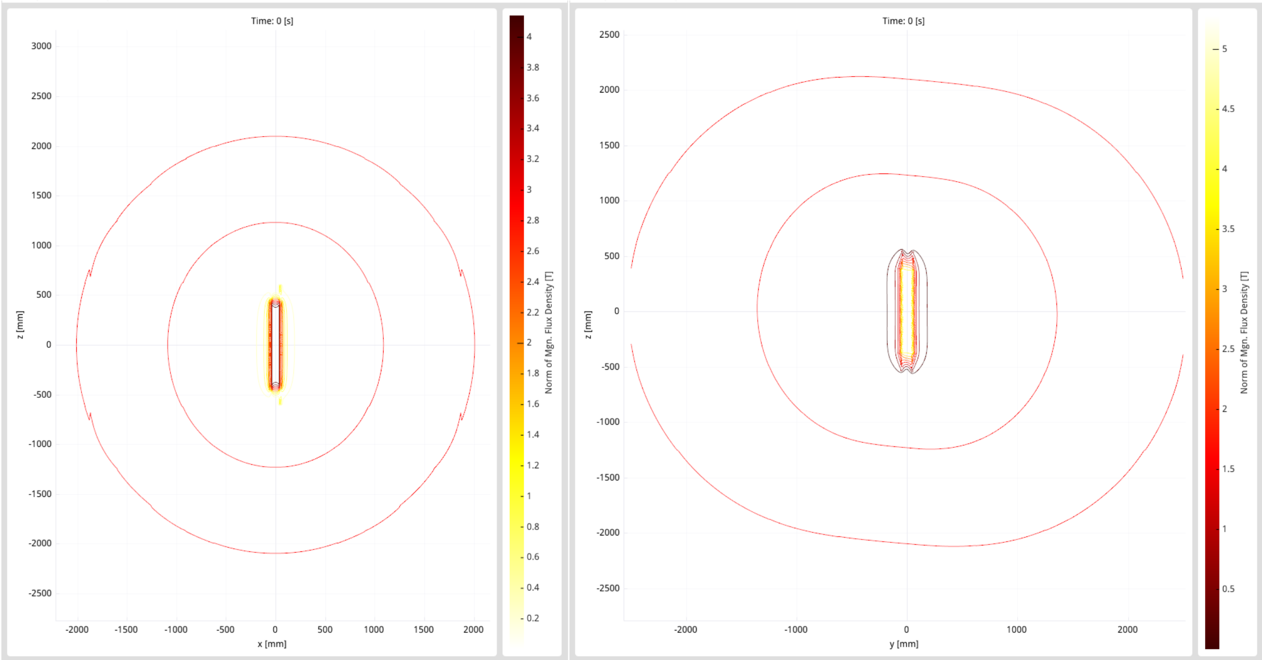

Figure 11: Magnetic flux 30 Gauss (inner) and 5 Gauss (outer) lines in the CCT main plans (xz) and (yz)

4 Mandrel and mechanical studies

The mandrel studies (size, material, groove machining…) same as mechanical studies will follow similar developments that for LTS CCT magnet. It has been decided for this report to not focus on those two parts. We can rely on the results of the deliverable D2 for the technology and material, which might be considered as preliminary results for the HTS. The particularities of HTS (like the conductor path without hardway bending or specific impregnation avoiding delamination) are currently studied for the machining possibility of CCT former and the tapes/cables windability. These parts will be developed in the engineering design of the CCT.

5 Future plans / Conclusion / relation to other IFAST work

We presented in this report the ongoing work on the HTS CCT design. We have a conductor path allowing reaching the expected performances using REBCO materials. We highlighted the major risk of the protection for this magnet and proposed two approaches to mitigate the risk. We also presented the complexity of including such materials in a CCT design (complex conductor path to avoid hardway bending, critical surface model for margins estimation, AC-losses in wide tapes, former machining…).

The future studies are ongoing or will start in order to prepare the engineering design. We will focus on:

- Winding study on no powered samples
- Evaluate the best solution for impregnation (resin, wax…) in relation with the study for the LTS CCT and the delamination issue of impregnated REBCO materials.
- Updating the design with an iron shell model
- Evaluate the AC, and radial current (for MI like option) losses
- Study the cable-to-cable electrical connection technology
- Order the HTS material to limit the supply delay impact on the project schedule

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