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How to cite

DE MATTEIS, E. et al. Conceptual design of an HTS Canted Cosine Theta dipole magnet for research and hadron therapy accelerators. In: IEEE transactions on applied superconductivity, 2024, vol. 34, n° 5, p. 4402505. doi: 10.1109/TASC.2024.3360210

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Publication DOI: 10.1109/TASC.2024.3360210

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Conceptual design of an HTS Canted Cosine Theta dipole magnet for research and hadron therapy accelerators

E. De Matteis, A. Ballarino, D. Barna, A. Carloni, A. Echeandia, G. Kirby, T. Lecrevisse, J. Lucas, S. Mariotto, J. van Nugteren, M. Prioli, L. Rossi, C. Senatore, M. Sorbi, S. Sorti, M. Statera, F. Toral, R.U. Valente.

***Abstract*—The European project IFAST's WP8 Innovative Superconducting Magnets aims to develop the technology of Canted Cosine Theta (CCT) magnets wound with High-Temperature Superconductors (HTS). Superconducting magnets could lower the size and cost of synchrotrons and gantries for research and hadron therapy. HTS materials can lead to higher magnetic fields with smaller cryogenic systems than LTS. However, they pose challenges in cable production schemes, magnet design, and cost. The project's final goal is to design a straight CCT-layout magnet with a central dipole field of 4 T, and a ramp rate of 0.4 T/s, but a lower ramp rate of 0.15-0.2 T/s is acceptable for the first step. The paper presents a preliminary design, discussing in particular the protection scheme with the magnet protection solutions for the conductor: one with two and the other with four HTS tapes. Both options generate 4 T of dipole field without an Iron shell, with at least 10 K of margin at an operational temperature of 20 K. To meet the time and budget constraints of the project, a simple cable based on a co-winding of commercial REBCO tapes is proposed. Protection is the most challenging aspect of the design and an adiabatic quench analysis has been used to determine the required thickness of copper stabilizer tapes to mitigate the risk of damaging the magnet during a quench. Finally, the paper evaluates AC and radial current losses during the magnet cycles, discussing the heat distribution and possible solutions for heat extraction.**

***Index Terms*—Superconducting magnets, HTS magnets, magnets for medical systems**

I. INTRODUCTION

PARTICLE beam therapy, similar to X-ray treatments, aims to selectively damage cancerous cells by exposing them to precise energy levels [1]. Carbon ions offer some advantages over protons and X-rays due to their energy distribution, which minimizes harm to surrounding healthy tissues, reducing collateral damage to patients. However, the size and cost of critical components like test facilities, accelerators, beamlines, and gantries pose limitations for both proton and ion therapies. Traditionally, achieving higher energies in accelerators necessitates larger physical dimensions. However, this approach doesn't apply straightforwardly to gantries, responsible for directing particle beams precisely. To overcome this challenge, the focus has shifted to superconducting ion gantries, which compact their size using enhanced magnetic field, making them more space-efficient. It's worth noting that while proton therapy centers are more widespread, ion gantries are operational in only two global locations. Europe's HIT (Heidelberg Ion Therapy center) [2] pioneered a rotating gantry but relied on normal conducting magnets. In Japan, NIRS's HIMAC [3] features a gantry with superconducting magnets, reducing both size and weight by half. Work Package 8 (WP8) within the I.FAST European project [4] is dedicated to advancing innovative superconducting magnets [5]. One of the core focuses of WP8 is the exploration of Canted Cosine Theta (CCT) [6] using HTS superconductors [7]–[9]. This is positioned as a primary goal, with prior discussions regarding the potential utilization of a combined function CCT approach based on low-temperature superconductors (LTS). Furthermore, WP8 actively engages with industries interested in gaining knowledge about CCT magnets and their potential applications, such as reducing the dimensions and cost of synchrotrons and gantries for cancer therapy. Indeed, the practical construction of the two magnet demonstrators involves the industries in various stages such as winding and magnet assembly, magnet testing, and validation. This paper outlines the conceptual design of a CCT dipole magnet using HTS REBCO tape superconductors, exploring geometry, quench protection, and AC losses [9]. Two geometries for a 4 T magnet demonstrator within the CCT framework are proposed. The magnetic design emphasizes field quality while avoiding harsh tape bending. Manufacturing considerations and thermal margins for conductors are discussed. Adiabatic quench analysis and AC loss calculations are presented for proposed designs, with mention of ongoing R&D on cabling and former construction.

This work was supported in part by the European Commission H2020-I.FAST grant n. 101004730, and in part by the project IR0000003 - IRIS supported by the NextGeneration EU-funded Italian National Recovery and Resilience Plan. (Corresponding author: E. De Matteis)

E. De Matteis, A. Carloni, M. Prioli, M. Statera, and R.U. Valente are with the Laboratory of Accelerators and Applied Superconductivity (LASA), National Institute for Nuclear Physics (INFN), Milan Section, Milano, Italy. (e-mail:ernesto.dematteis@mi.infn.it)

A. Ballarino and G. Kirby are with CERN CH-1211 Geneva 23 Switzerland.

D. Barna is with Wigner Fizikai Kutatokozpont, Budapest, Hungary

A. Echeandia and J. Lucas are with the Elytt Energy, Madrid, Spain

T. Lecrevisse is with Commissariat à l'énergie atomique et aux énergies alternatives, Saclay, France

S. Mariotto, L. Rossi, M. Sorbi, and S. Sorti are with the Laboratory of Accelerators and Applied Superconductivity (LASA), National Institute for Nuclear Physics (INFN), Milan Section, Milano, Italy and Department of Physics, University of Milan, Milan, Italy.

J. van Nugteren is with Little Beast Engineering, Zurich, Switzerland

C. Senatore is with the University of Geneva, Geneva, Switzerland

F. Toral is with Centro de Investigaciones Energeticas Medioambientales y Tecnologicas, Madrid, Spain

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TABLE I
MAIN PARAMETERS FOR THE HTS CCT DEMONSTRATOR MAGNET.

Parameters	Values	unit
Magnet type	CCT	-
Geometry	Straight	-
Central magnetic field B0	4	T
Magnetic and physical length	0.8, 1	m
Bore diameter	80	mm
dB/dt	0.2 - 0.4	T/s
Operation temperature	10 - 20	K
Loadline margin static	20 - 25	%
Superconductor	ReBCO tape	-

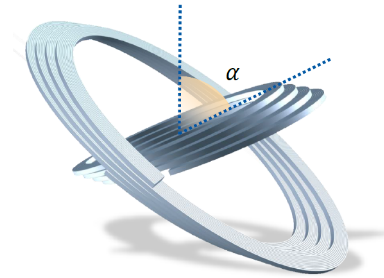

Fig. 1. A rendering showing a few turns of the winding geometry of the HTS CCT coil.

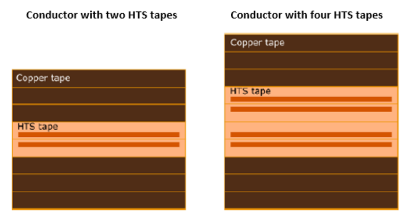

Fig. 2. Schematic drawing of the conductor design with two HTS tapes on the left and four HTS tapes on the right. The number and the width of copper tapes that sandwich the HTS tapes should be based on the maximum hot-spot temperature after a quench event.

II. MAGNET PARAMETERS

Within the framework of WP8 in the European I.FAST project, the primary objective is to investigate the application of Canted Cosine Theta in conjunction with High-Temperature Superconductors (HTS). This project centres on the development of a superconducting rotating gantry designed specifically for carbon ions with a beam rigidity of 6.6 Tm [10], as other European programs HITRIplus [7], [11] and SIG [12]. The key innovation lies in reducing the dimensions of the gantry while concurrently increasing the attainable magnetic field strength to 4 Tesla [13], [14]. To simplify the technical challenges associated with HTS, the magnet's geometry is designed to be straight. As shown in Tab. I, the design parameters include a maximum length of 1 meter and a bore diameter of 80 mm. Notably, the most demanding parameter to address is the magnetic field ramp rate, which must fall within the range of 0.2 to 0.4 Tesla per second. The operational temperature range for this setup is 10 to 20 Kelvin, necessitating the use of REBCO tape as the chosen superconducting material. In summary, the WP8 of the European IFAST project aims to explore the integration of Canted Cosine Theta with HTS technology, with specific magnet parameters geared towards a compact superconducting gantry for carbon ions.

III. CONDUCTOR GEOMETRY AND CONFIGURATIONS

The CCT magnet geometry is described by a space curve $\vec{R}(\theta)$ along the inner radius:

$$\vec{R}(\theta) = \rho(\theta)\cos(\theta)\hat{e}_x + \rho(\theta)\sin(\theta)\hat{e}_y + ... \\ ... + (A_i(\theta)\sin(2\pi n\theta + \omega))\hat{e}_z \quad (1)$$

It adapts to non-round apertures, involving parameters like $\rho(\theta)$ and $A_i(\theta)$. Derivatives and Frenet-Serret equations guide conductor orientation along the curve, for details, refer to [15].

The design of CCT coils involves skew winding angles of α = 60° for the inner layer and 50° for the outer layer to equalize coil-end lengths and cancel axial fields (Fig. 3). Tapes are laid flat due to soft-way bending, resulting in a minimal winding pitch ω (calculated as $\omega = w_{tape} + w_{rib} * cos(\alpha)$) with a chosen pitch of 10 mm. This leads to rib thicknesses of 0.98 mm for the first layer and 2.4 mm for the second layer.

To achieve a 4 T field, each conductor must carry 22 kA, which exceeds the 2 kA limit (upper limit to avoid excessive heat load from the current leads). Using cables with multiple tapes in parallel, such as 2 tapes for 50% current capacity or 4 tapes for 75% capacity (Fig. 2), is recommended to mitigate possible defects of the tape. Calculations based on Fujikura FESC-SCH04 [16] indicate the need for 23 cables per former at 970 A for the two-tape option and 11 cables at 1990 A for the four-tape option to maintain a 10 K temperature margin (see sections V and VI).

Extra copper stabilizer material is needed to share current during quench events, with a preference for type-0 pairs facing each other. For the four-tapes cable, tape orientation variations should be investigated. Large copper layers on the superconductor side are discouraged due to potential shear forces during Lorentz-induced deformation. To maximize current sharing, copper tapes should be soldered to HTS and to themselves or maintained in good electrical contact. Soldering should occur inside the cable to avoid shorts. As the bending radius is approximately 50 mm, tapes cannot be soldered before winding, requiring winding from separate spools and subsequent soldering. The proposed conductor design includes two or four HTS tapes with HTS sides facing each other in pairs. Copper stabilizer tapes are stacked on both sides of the HTS tapes (Fig. 2).

IV. MAGNETIC DESIGN

To address field errors introduced by the non-right-angle orientation of the tape with respect to the former, the coil's radius can be described using a Fourier series with coefficients a_n and b_n as given in the following equation:

$$\rho(\theta) = \sum_{n=0}^{\infty} (a_n \cos(\pi n\theta) + b_n \sin(\pi n\theta)) \quad (2)$$

Coefficients are optimized to minimize field harmonics, ensuring planar coil turns for a valid Frenet-Serret frame

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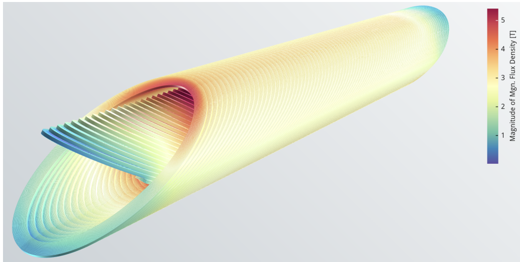

Fig. 3. Magnetic flux density on the conductor modelled using RAT [18].

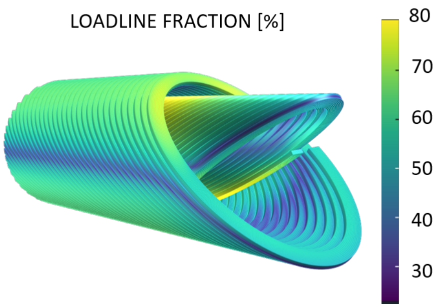

Fig. 4. 3D loadline margin fraction on the conductor for the 4 tapes configuration.

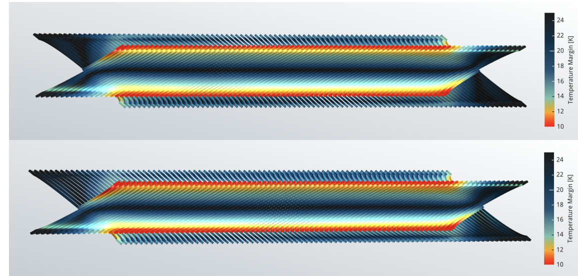

Fig. 5. Thermal margin of the two and four HTS tape designs.

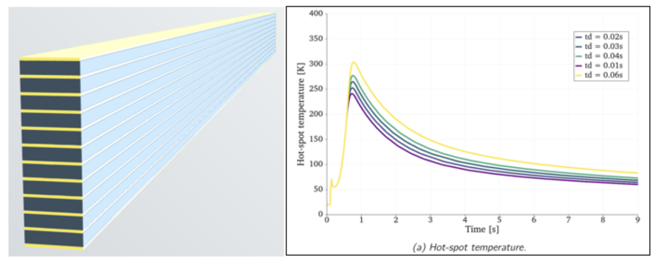

Fig. 6. The two-dimensional piece of conductor for quench simulations, and the hot spot temperature for different detection time, 700 μm of copper stabilizer, and 0.3 V of quench detection voltage .

without hard bending [17]. The a_1 coefficient represents the CCT layer radius (44 mm for the inner layer and 64 mm for the outer layer). Using a_4 = 80 μm and a_6 = -15 μm in both layers effectively reduces all harmonics below 1 unit.

Since the conductor experiences a magnetic field at various angles due to the orientation of the tapes with respect to B (Fig. 3), it's common to consider the critical current under a transverse field for loadline margin assessment. Using the Fujikura FESC-SCH04 tape, which can handle 660 A at 20 K under a 5 T transverse field, results in a 25% margin. This ensures that in the 4-tapes configuration, even if a local defect occurs in one tape, operations near to nominal conditions can still be maintained (Fig. 4).

V. Thermal Design and Quench Protection

Another crucial requirement in the coil design is the need for rapid ramping of the magnet. To meet this requirement, a minimum thermal margin of 10 K is imposed on the coil's design, maintaining this margin at an operating temperature of 20 K. This thermal margin constraint also impacts the determination of the number of cables within a CCT slot. Specifically, higher critical currents of the HTS tapes and a greater number of HTS tapes per cable lead to an increased thermal margin. For this study, the properties of Fujikura's FESC-SCH04 were selected once again. This tape's characteristics are based on measured data, and current sharing is considered in the calculation of the temperature margin. This means that current can freely distribute across the width of the tape. Figure 5 illustrates the temperature margin within the coil for both two and four tapes configurations, respectively. It's noteworthy that the margin throughout the coil pack consistently exceeds 10 K and is significantly larger in most parts of the coil.

A 2D quench analysis simulation (RAT and Racoon software [18]) determined the necessary copper stabilizer quantity in CCT coils (Fig. 6). Considerations included inductance, transverse magnetic field effects, and copper's magnetoresistance. Results showed that increasing copper stabilizer reduced hot-spot temperatures. Optimal settings for quench detection and protection were found: a 0.3 V quench detection threshold and a 0.02 s protection delay (Fig. 6). Table II displayed hot-spot temperature vs. copper stabilizer thickness for two and four HTS tapes per sub-layer. More copper stabilizer led to lower temperatures. For four tapes, 700 μm of copper stabilizer reached a maximum 250 K hot-spot temperature, similar to two tapes with 350 μm. Generally, 250 K was deemed a safe limit for HTS coil hot-spot temperature. Efficient current extraction and system protection used a 500 V protection voltage. Importantly, simulations showed that increasing copper stabilizer improved protection without significantly increasing the magnet system's cost.

TABLE II
Hot-spot temperature versus quench detection threshold for different copper stabilizer thicknesses. The voltage threshold used during each scan is given in the table.

	Two HTS tapes	Four HTS tapes	
	350 µm	600 µm	700 µm
V_{Th}	0.2 V	0.2 V	0.3 V
$t_d[s]$	$T_{hot-spot}[K]$	$T_{hot-spot}[K]$	$T_{hot-spot}[K]$
0.01	224	224	241
0.02	235	238	252
0.03	242	252	264
0.04	253	268	277
0.05	263	284	290
0.06	275	302	304

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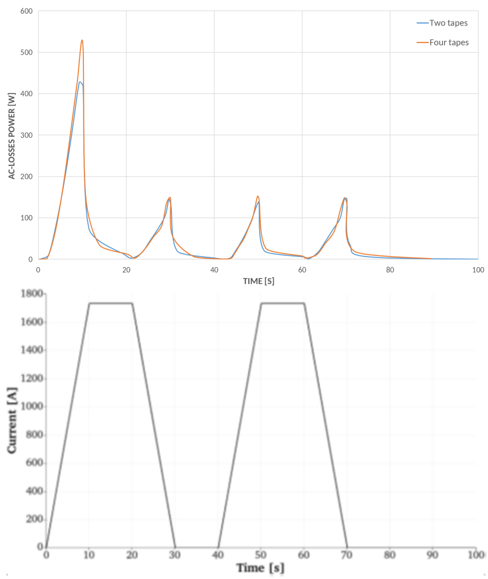

Fig. 7. The AC-losses in the two-tape (blue) and the four-tape (orange) design of the HTS CCT demonstrator, and the current profile during the ramping of a sub-scale model for the AC-loss calculations. The current is cycled two times for both the two and the four-tape case.

VI. AC LOSSES

To determine whether to use two or four tapes in the CCT design, an assessment of AC losses during rapid magnet ramping from 0 T to 4 T in under 10 seconds was conducted (Fig. 7). These losses occur due to screening currents in the HTS tapes and are crucial for assessing the cooling power requirements.

A model was employed to simulate AC losses during the magnet ramping process. In this model, individual tapes were simulated one by one. To optimize the process, only 22 turns were simulated, and the outcomes were extrapolated to estimate losses for the entire 84-turn coil. AC losses were calculated in Raccoon [18] using the formula $P_{AC} = \vec{J} * \vec{E_R}$, where P_{AC} represents AC loss power, $\vec{J}$ is the current density, and $\vec{E_R}$ is the resistive part of the electric field $\vec{E}$. The current profile for this analysis involved cycling between 0 T and 4 T twice. The results indicated that both the two and four-tape designs had peak AC losses of 50 watts on average during a ramp, manageable by cryocoolers. The peak losses could be spread over time by the system's heat capacity or augmented with a copper block if needed. Despite having twice as many HTS tapes in each slot, the two-tape design had comparable AC losses to the four-tape design due to differences in insulation between the tapes. These results suggested that hysteresis losses predominantly contributed to AC losses in this design.

VII. CABLING AND MANUFACTURING

To prevent excessive shear stress during coil winding, soldering the tapes inside the cable post-winding is crucial. Achieving this involves placing the entire coil wound on the former into an oven, keeping the temperature below 200°C to avoid HTS degradation. Standard tin-lead solder, with a melting point around 180°C and good electrical and mechanical properties, is a suitable choice. Alternatively, low temperature solders are an option, although more complicated to apply. To prevent shorts from solder bridging in the CCT slot, propose separate heat treatments for each cable. Apply Stycast and polyimide between cables to create a protective boundary, securing both the polyimide tape and cables. While cabling with a two-tape configuration is time-consuming, it represents a reasonable manufacturing compromise. For the former, insulating materials like G11 or coating a metal surface before winding could be ideal for electrical contact but might not be optimal for extracting AC losses during operation. Aluminum-bronze material could provide a balanced solution. Different former geometries, considering the conductor's non-circular cross-section, should be explored.

Regarding R&D efforts, progress is being made in cabling short stacks of copper tapes with polyimide insulation in a two-tape configuration, sacrificing some reliability for simplification. Short former tests are ongoing to demonstrate the machinability of aluminum-bronze materials. The challenge lies in determining the geometry and number of splices.

VIII. CONCLUSIONS

This paper comprehensively analyzes the CCT (Canted Cosine Theta) demonstrator based on High Temperature Superconductors (HTS), covering conductor properties, magnetism, manufacturing, thermal performance, protection mechanisms, and power losses. The HTS demonstrator employs a CCT layout to address the limitations of flat REBCO HTS tapes, minimizing bending stress using the Frenet-Serret frame. Two 4 T magnet demonstrator geometries are proposed: one with two 4mm-wide tapes, 23 cables per former slot at 970 A, and another with four 4mm-wide tapes, 11 cables per former slot at 1990 A. Soldering HTS and copper stabilizer tapes together is required for current sharing, necessitating separate winding before soldering on the former. Adiabatic quench analysis determines copper stabilizer tape thicknesses of 350 μm and 700 μm for two-tape and four-tape designs, respectively, to maintain peak temperature below 250 K with specified quench parameters. Precise field quality is achieved by controlling Fourier series coefficients describing the coil's radius. Average AC-losses during operation for both designs are approximately 50 W, suitable for a cryocooler-based conduction cooling system at 20 K. As for the manufacturing aspects, shear stress during coil winding could be prevented with soldering below 200°C. The next steps involve the production of aluminium-bronze formers, the two-tape cable splicing and winding procedure, and FEM simulations to validate the magnet components from both a cryogenic and mechanical point of view.

ACKNOWLEDGMENTS

The authors gratefully acknowledge H2020-I.FAST Coordinator, Maurizio Vretenar, for his continous support. The writing of this paper work were made possible thanks to the project IR0000003 - IRIS supported by the NextGeneration EU-funded Italian National Recovery and Resilience Plan with the Decree of the Ministry of University and Research number 124 (21/06/2022) for the Mission 4 - Component 2 - Investment 3.1.

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