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SUPERCONDUCTING MAGNETS TECHNOLOGY FOR A EUROPEAN HEAVY ION GANTRY*

M. Prioli†, E. De Matteis, L. Rossi[1], C. Santini, S. Sorti[1], R. U. Valente, INFN-LASA, Milano, Italy
T. Gusvitskii, Sapienza University of Rome, Italy
E. Bianchi, S. Farinon, F. Levi, INFN Genova, Italy
G. Ceruti, L. Gentini, D. Perini, CERN, Geneva, Switzerland
J. Munilla, F. Toral, CIEMAT, Madrid, Spain
M. Pullia, E. Felcini, CNAO Foundation, Pavia, Italy
D. Barna, P. Sari, Wigner Research Centre for Physics, Budapest, Hungary
[1]also at Università degli Studi di Milano, Italy

Abstract

Various initiatives in Europe have been launched to study superconducting magnets for a rotatable gantry suitable to deliver up to 430 MeV/u carbon ions for hadron therapy. Different technologies and layouts are being considered: the baseline solution is developed within the EuroSIG collaboration and consists of a strongly curved cos-θ dipole based on the classical NbTi superconductor. The HITRIplus and I.FAST projects are dedicated to the study of the novel Canted Cosine Theta (CCT) dipoles based on NbTi and also HTS. Common design targets were set to allow a direct comparison of the different solutions: 4 T central field in an 80 mm bore, a curvature radius of 1.65 m, and a ramp rate of 0.15 – 0.4 T/s.

The progress in the construction of four different demonstrator magnets is discussed and a preliminary comparison is proposed.

INTRODUCTION

The development of ion gantries is one of the promising routes to increase the quality of cancer treatments through non-coplanar ion irradiation. The main obstacle is the cost of these devices which justifies their present limited number [1–3] and, as a first approximation, is related to their significant size and weight.

A European effort for the technological development of ion gantries targeted to the reduction of their size, weight, and cost is presently being made [4]. The programs with this scope include SIG [5–7], (the Superconducting Ion Gantry project) framed in the EuroSIG collaboration between INFN, CERN, CNAO, and MedAustron with the aim of exploring a cos-θ LTS magnet design. Moreover, the *HITRIplus* Work Package 7 (WP7) dedicated to the study of the gantry layout, and the *HITRIplus* and *IFAST* WP8, targeted to alternative technological solutions for the superconducting magnets (Canted Cosine Theta (CCT), high-temperature superconductors, combined function magnets) [4, 8–12].

The core of these programs, coinciding with the focus of this paper, is the development of superconducting magnet technology for ion gantries and the main challenge is the remarkable curvature required for gantries. It is worth noting that they are part of a much broader effort on innovative solutions for the next-generation ion gantries, such as an optimized optical and mechanical gantry layout, a dedicated cooling system without liquid helium, an advanced thermal design for conduction-cooled magnets, downstream scanning magnet systems and their power converters, dedicated dose delivery, and range verification systems for ions.

COMMON MAGNET PARAMETERS

After several iterations with the gantry optical design discussed in [13–15], we defined the parameters of the prototype and demonstrator magnet for the ion gantry reported in Table 1. These parameters are a common baseline for all programs pursuing different technological solutions (cos-θ and CCT coil design and LTS and HTS conductors) in a way that a direct comparison among them will be possible for the definition of the optimal layout for the final magnet prototype.

Table 1: Design parameters for the demonstrator and prototype magnets.

Parameter	**Demo.**	**Prot.**
Dipole field (T)	4	4
Radius of curvature (m)	1.65	1.65
Aperture (mm)	80	80
Field ramp rate (T/s)	0.15	0.4
Angular sector (°)	30	45

SIG AND EuroSIG

Program Scope

The specific scope of SIG WP2, framed in the EuroSIG SDM-c addendum (curved superconducting demonstrator magnet), is the design, manufacturing, and testing at cold of a curved dipole demonstrator magnet [5–7] with cos-θ coils and NbTi Rutherford cable [16] (see the preliminary

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† marco.prioli@mi.infn.it

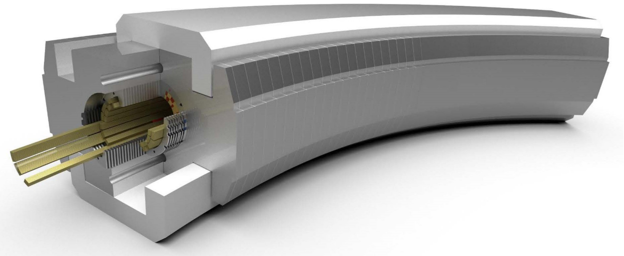

Figure 1: Preliminary rendering of the SIG demonstrator magnet courtesy of FEAC Engineering, Greece.

rendering in Fig. 1). SIG focuses on leveraging the characteristics of accelerator magnets to design effective gantry dipole magnets. Two key differences emerge: the smaller curvature radius and the thermal challenges, including higher field ramp rates and heat extraction requirements.

The final specifications for the EuroSIG collaboration include both the curved geometry and the conduction cooling feature, but two different programs are dedicated to their development. SIG prioritizes the study of windability of the concave coil and assembly of the curved structure, compatible with the conduction cooling feature, but not explicitly optimized for this target. The final goal of SIG is a powering test of the demonstrator SDM-c in liquid helium and a measurement of the actual heat conduction performance may occur at the end of the project. A parallel program at CERN addresses the indirect cooling issues by constructing the straight thermal demonstrator magnet SDM-s sharing the cross-section with SDM-c.

Program Status

The conceptual design of the SIG SDM-c magnet was completed in 2023 [7] and a review by a panel of international experts was called in early 2024. The reviewers assessed the quality, quantity, and completeness of the work and recommended to go ahead with curved winding tests. The outcome of the thermal design is that the low-temperature margin calls for an accurate simulation of the thermal contacts and, possibly, an experimental activity for their characterization. As for the mechanical design, an activity to deepen the study for an easier magnet assembly and to develop a detailed 3D analysis is started. The reviewers recommended foreseeing a measurement of the AC loss during the first cold test in liquid helium.

The planned coil manufacturing technique is based on a double pancake with intermediate curing of each layer using a polymeric binder and with a final impregnation through the epoxy resin to satisfy the conduction cooling requirement. The alternative of winding two separate layers is not adopted to avoid a complicated interlayer splice in a ramped magnet. This technique was validated for the Hi-Lumi LHC nested orbit corrector magnet [17–19], and the most critical point is its adaptation to the curved geometry of SDM-c. Preliminary winding and curing experimental tests were carried out on the SIG coil and cable geometry and they confirm the validity of this procedure.

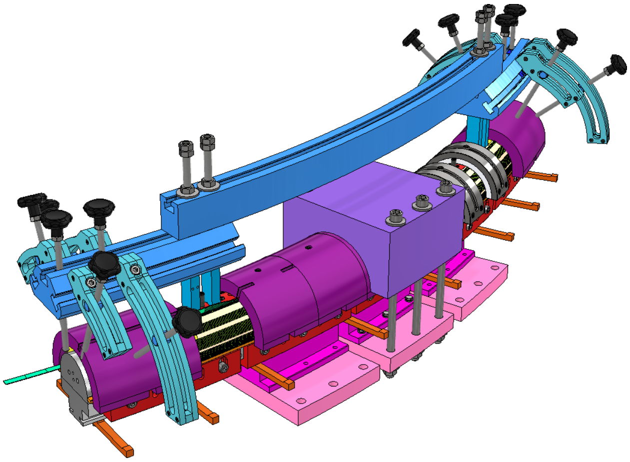

Figure 2: Gradual replacement of the winding tooling with the curing one on the winding table. One curing mold (violet) is placed on top of the curing fillers (magenta).

The tooling for winding, curing, and impregnating the curved coil is designed and being procured. The winding test is planned to start in mid-2024. The gradual replacement of the winding tooling with the curing one is shown in Fig. 2. It replicates a simple curing press directly on the winding table to minimize the coil handling tooling.

HITRIplus AND I.FAST

HITRIplus

The HITRIplus collaboration, consisting of 22 institutes, has been granted €5 million to advance technologies in ion therapy facilities across Europe. Work Package 8 (WP8) within this collaboration focuses on devising solutions for superconducting magnets applicable to ion therapy gantry and synchrotron systems, with a beam rigidity of 6.6 Tm. This collective effort entails the complete process of designing, manufacturing, and testing a prototype magnet. The chosen design employs a NbTi superconductor wound in a CCT configuration, utilizing conduction cooling with impregnation (Fig. 3).

A significant challenge is the curved design requirement with a tight bending radius of 1.65 m while maintaining suitable field quality for accelerators or beam lines. The design centers around a rope cable conductor with a proposed 2×7 ropes-in-groove layout, consisting of 6 low-loss Nb-Ti strands and a central copper core. Each rope carries approximately 1.6 kA to minimize excessive current loss [20]. An algorithm is employed to optimize the CCT path, determining the optimal current density distribution and 3D winding paths. Yoke optimization involves geometric modifications to enhance field quality.

Fabrication addresses challenges in the former and support structure. Aluminum bronze is chosen for the former due to its balanced properties and favorable manufacturing

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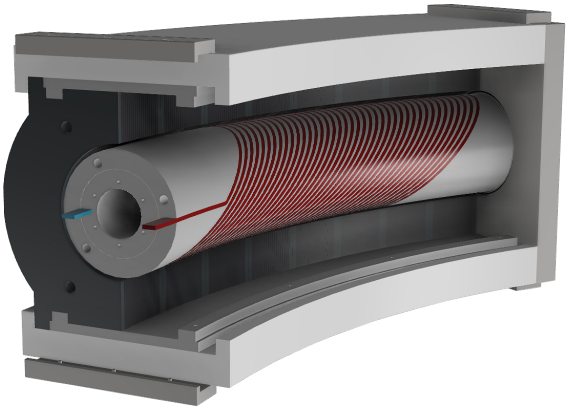

Figure 3: 3D view of the curved HITRIplus demonstrator magnet.

characteristics. The fabrication process involves machining subsections joined using pins or glue, with ongoing validation tests. For the support structure, a vertically split iron yoke is proposed to limit the deformations and stresses of the CCT magnet [21]. Two alternatives are explored: tapered iron laminations and splitting the iron yoke into sectors both with aluminum clamps (Fig. 3). Both aim to manage Lorentz forces during magnet operation. The final decision on the assembly gap and support structure is pending.

Ongoing progress is focused on conductor finalization, winding tests, wax impregnation trials, and the construction of the curved former with a streamlined assembly of components. The construction of the magnet addresses challenges, emphasizing efficient heat extraction from both superconductor and former, and underscores the development of innovative solutions, particularly in the absence of liquid helium cooling.

I.FAST

The I.FAST project, standing for Innovation Fostering in Accelerator Science and Technology, is committed to driving innovation in the field of accelerator science and technology. A specific work package within this program is dedicated to advancing innovative superconducting magnets. The primary objective of this work package is to develop High-Temperature Superconducting (HTS) technology for application in particle therapy gantry and synchrotron magnets, in line with the sustainable technology goals of SEEIIST (South East European International Institute for Sustainable Technologies).

In pursuit of advancing superconducting magnets, I.FAST Work Package 8 (WP8) outlines key objectives and current progress. These goals include establishing a permanent European Strategy Group to collaborate with global partners in formulating a European strategy for HTS magnets in accelerators and enhancing industry engagement in this transformative technology. Another goal is to explore the CCT configuration utilizing HTS superconductors, preceded by a CCT based on Low-Temperature Superconductors (LTS) to facilitate knowledge transfer to interested industries [11]. The final objective focuses on constructing two demonstrators, emphasizing winding, magnet assembly, testing, and validation.

The first demonstrator utilizes a combined function CCT based on LTS (Fig. 4), achieving critical dipole and quadrupole strengths crucial for CCT evaluation [22]. Heat extraction management from the superconductor and former is a primary challenge, with the demonstrator featuring straight geometry, an operational temperature of 4.5 K, and a nominal current of 1.5 kA [20]. Notably, the formers are constructed from Aluminum-Bronze and undergo wax impregnation. Iron yoke omission distinguishes this prototype.

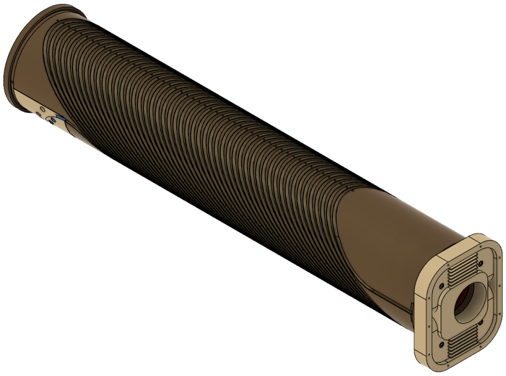

Figure 4: 3D view of the first I.FAST NbTI CCT demonstrator: splice box and outer former.

The second demonstrator employs CCT based on HTS (REBCO tape, 4 mm wide), achieving dipole strength with two options for cable configuration with 2 and 4 tapes (Fig. 5) [12]. An adiabatic quench analysis suggests that the copper stabilizer tape thicknesses of 350 µm and 700 µm for two-tape and four-tape designs, respectively, ensure a peak temperature below 250 K with specified quench parameters. The AC losses during operation are on average 50 W at 0.4 T/s, a value compatible with a 20 K conduction cooling system, eliminating the necessity for helium gas.

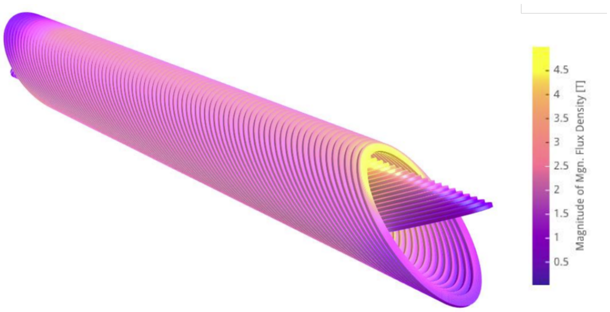

Figure 5: Magnetic flux density on the conductor of the HTS CCT (I.FAST) .

COMPARISON

The salient magnet design features for the four European programs discussed in this paper are listed in Table 2. The

Table 2: Comparison of the salient magnet design features for four European programs on the heavy ion gantry technological development.

Parameter	SIG	HITRIplus	I.FAST LTS	I.FAST HTS
Coil type	Cos−θ	CCT	CCT	CCT
Radius of curvature (m)	1.65	1.65	∞	∞
Quadrupole gradient (T/m)	0	0	5	0
Magnetic length (m)	0.86	0.8	0.8	0.8
Current (A)	2770	1670	1540	980
Operational temperature (K)	5	4.7	4.7	20
Superconductor	NbTi	NbTi	NbTi	REBCO
Cable type	Rutherford	Rope	Rope	Stack
No. strands/tapes	36	6	6	2
Insulation	Quartzel	Poliester	Poliester	Kapton
Impregnation	Epoxy	Wax	Wax	Wax

coil design has a strong impact on all project aspects, from the technical implementation to the magnet cost. From a technical point of view, the programs did not reveal potential show-stoppers, and both cos−θ and CCT layouts can be adopted for a superconducting magnet for ion gantries. The cos−θ LTS design is a mature technology due to the developments in the accelerator magnet field while the CCT option, especially for the HTS version, has a lower technology readiness level. Concerning the adaptation to the small curvature radius, custom, and complex tooling has to be developed for the cos−θ design, while for the CCT the complexity lies in the manufacturing of the curved former. The CCT has a lower operational current given by the series connection of multiple ropes/tapes, an advantage for the lower heat generated in the HTS current leads. The disadvantage is the need for several splices among the conductors addressed with a dedicated splice box. Moreover, a clear advantage for the HTS version is the 20 K operational temperature which allows an AC loss approximately one order of magnitude larger than the LTS versions given the higher cooling efficiency at that temperature.

An advantage of the CCT layout is the limited number of winding tooling needed w.r.t. the cos−θ which might have an impact on the final magnet cost. While it will be simple to compare the costs of the different demonstrators once completed, a dedicated cost model will be needed to scale the cost of the demonstrator to real-scale prototypes with all features embedded, and consider a total production of four magnets plus one spare for a gantry.

CONCLUSION

This paper presented the status of three different European programs for the technological development of superconducting magnets for an ion gantry and the main features of their four demonstrators. Both cos−θ and CCT layouts can be adopted for the final prototype with the advantages and disadvantages partially discussed in this paper. A comprehensive evaluation of the pros and cons of each solution will be possible only at the end of the programs, foreseen in 2025. The final choice will be made based on the success of each program, the technical gap between the demonstrated features and the characteristics needed for the final prototype, and the cost of the magnets for the gantry.

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