Journal of Physics: Conference Series

Magnet Technology and Design of Superconducting Magnets for Heavy Ion Gantry for Hadron Therapy

To cite this article: L. Rossi *et al* 2024 *J. Phys.: Conf. Ser.* **2687** 092009

Magnet Technology and Design of Superconducting Magnets for Heavy Ion Gantry for Hadron Therapy

L. Rossi[1,2], D. Barna[3], A. G. Carloni[2], E. De Matteis[2], S. Farinon[4], E. Felcini[5], E. Gautheron[6], M. Karppinen[6], G. Kirby[6], T. Lecrevisse[7], R. Musenich[4], D. Perini[6], M. Prioli[2], M. Pullia[5], S. Sorti[1,2], D. Tommasini[6]

[1]Università degli Studi di Milano, Milan, Italy.
[2]INFN-LASA, Milano, Italy
[3]Wigner Research Centre for Physics, Budapest, Hungary.
[4]INFN Genova, Italy.
[5]CNAO Foundation, Pavia, Italy.
[6]CERN, Geneva, Switzerland.
[7]CEA – IRFU, Gif-sur-Yvette, France.

E-mail: lucio.rossi@mi.infn.it

Abstract. Various initiatives in Europe have been launched to study superconducting magnets for a rotatable gantry suitable to deliver up to 440 MeV/A carbon ions for hadron therapy. One initiative is led by INFN inside an agreement with CERN, CNAO, and MedAustron aiming at designing and manufacturing a strongly curved cos θ dipole rated for 4 T central field and with a ramp rate of 0.15-0.4 T/s. Here we explore the suitability of dipole technology derived from HEP collider for a rotatable gantry that poses severe conditions on the thermal design (indirectly cooled coils). A second one is in the frame of the European program H2020-HITRIplus-WP8, aimed at exploring the feasibility of using the novel Canted Cosine Theta (CCT) concept to produce a superconducting dipole with similar characteristics. The scope is to design and built one or two prototypes with Nb-Ti rope, to see if this route could be a viable alternative. Finally in the European collaboration H2020-I.FAST-WP8 we are exploring both CCT in combined function design (dipole + quadrupole, in Nb-Ti) and the use of HTS (REBCO tapes) with CCT dipole layout, pursuing the design manufacture of small prototypes with European Industry. If HTS will be found successful, it will be a great benefit for the cryogenic design of the magnet system.

1. Introduction

Particle beam therapy, in particular with ions like carbon, aims to destroy tumour cells [1], minimizing collateral damage to the patient. Despite the benefits of using particle therapy, its application is limited by the size and cost of accelerator and beamline facilities, particularly for gantries. While accelerator facilities typically increase in radius to achieve higher energies, the same is not easily achievable for gantries, which are necessary for improving treatment efficiency with multiple-direction beam delivery. This makes superconducting ion gantries a preferred solution, as they allow for a reduction in size while increasing the available magnetic field flux. The HIT (Heidelberg Ion Therapy center) [2] was the first center in Europe to utilize a rotating gantry based on normal con-ducting magnets, while the HIMAC of NIRS in Japan was the first to use a gantry with superconducting magnets, resulting in a size and weight reduction by a factor of two [3]. Several initiatives in Europe aim to develop super-conducting magnets for a rotatable gantry that can deliver high-energy carbon ions of maximum rigidity of 6.6 Tm for hadron therapy. One project, SIG [4-9], led by INFN with collaboration from CERN, CNAO, and MedAustron, is designing a strongly curved cosθ dipole with a central field rating of 4 T and a ramp rate of 0.15-0.4 T/s. Another initiative, H2020-HITRIplus-WP8 [7, 11], partly supported by the EU, aims to explore the feasibility of using the CCT concept to produce a super-conducting dipole with similar characteristics, while the H2020-I.FAST-WP8[7, 12] collaboration, also partly supported by the EU, is exploring CCT in combined function design and the use of HTS (REBCO tapes) with CCT dipole layout. These projects seek to design and manufacture small prototypes to determine the viability of these technologies, which could offer significant benefits to the cryogenic design of the magnet system.

2. The SIG project

SIG (Superconducting Ion Gantry) is an INFN-driven project inserted in the general framework of a four-party agreement between INFN, CNAO, CERN, and MedAustron [4-9]. The scope of the project is to contribute to the development of key technologies for an ion gantry including a 4 T superconducting curved dipole demonstrator magnet, a downstream scanning magnet system, and dose delivery and range verification systems for ions. The main project's focus is on the dipole magnet whose aim is to demonstrate the feasibility of winding, assembling, and testing an accelerator magnet type made of cosθ coils with a low curvature radius of 1.65 m. The main parameters of the SIG demonstrator are reported in Table 1. Its magnetic angle will be 30° instead of the 45° required for the final prototype, and its ramp rate has been reduced to 0.15 T/s from the initial 0.4 T/s target since the available superconducting cable is not optimized for low-loss. However, the conductor loss for the demonstrator at 0.15 T/s is equivalent to the one for the prototype at 0.4 T/s thanks to the expected dynamic performances of the optimized cable, already achieved in past programs [10, 13, 14].

Table 1. Main Parameters of the SIG Demonstrator

Parameter	Value	Unit
Dipolar field	4	T
Radius of curvature	1.65	m
Aperture	80	mm
Field ramp-rate	0.15 – 0.4	T/s
Angular sector	30 – 45	°
Operational current	2.79	kA
Operational temperature	5	K

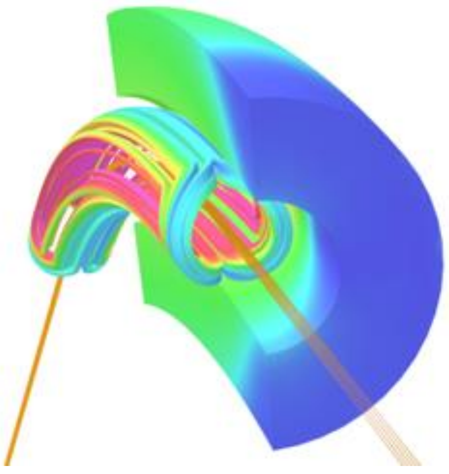

Figure 1. 3D layout of the coils and one-half of the iron yoke. The trajectory of the reference particle is also highlighted.

2.1. Main Features of the SIG Demonstrator
After an extensive exploration of the parameter space of the demonstrator magnet [5, 9], we identified an optimal 2D and 3D electromagnetic design, whose main features are:
- NbTi Rutherford cable with 36 strands of ϕ 0.48 mm,
- Cosθ coil with 7 blocks arranged into two layers with 4.46 T peak filed on the conductor,
- A relatively low operational current of 2.79 kA to limit the loss in the conduction-cooled current leads,
- A conductor loss of about 1 W/m with a ramp rate of 0.15 T/s, leading to a peak temperature of 4.97 K.

The 3D layout of the coils and one-half of the iron yoke is shown in Fig. 1, and the 2D peak temperature distribution is shown in Fig. 2. The highest temperature difference is in the stainless-steel collars and the impregnation of the coils ensures a good temperature homogeneity. A parallel program led by CERN is dedicated to the study of the thermomechanical design to improve the thermal contacts for the challenging conduction cooling feature.

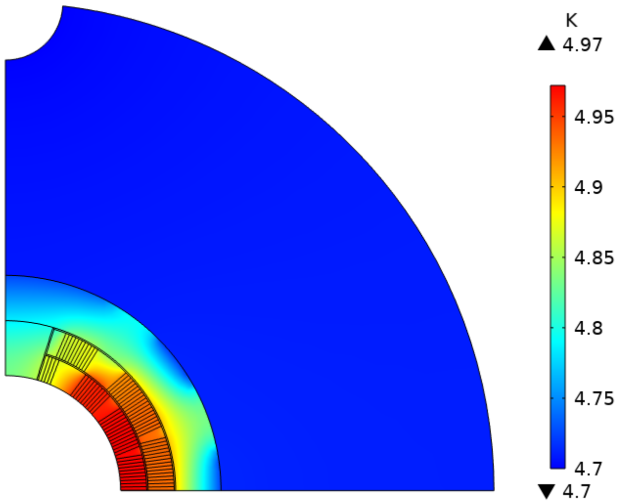

Figure 2. Maximum temperature during operation in the 2D cross-section of the magnet. The iron yoke is supposed to be isothermal at 4.7 K.

3. HITRIPLUS and I.FAST Projects
A European collaboration, funded by the EC-Horizon2020 HITRIplus and I.FAST programs [7,11,12], is currently investigating next-generation ion therapy magnets for both gantry and accelerator (synchrotron) applications. The collaboration has secured funding for work packages focused on superconducting magnet development. The Heavy Ion Therapy Research Integration plus (HITRIplus) [11] collaboration, consisting of 22 institutes, has been awarded a €5M grant to develop novel technologies for the improvement of ion therapy facilities in Europe, with a work package on the development of superconducting magnets for a light rotatable gantry and an accelerating synchrotron.

The program is to be carried out over four years (2021-2025) to strengthen Europe's position in cancer treatment with ion beams. The I.FAST (Innovation Fostering in Accelerator Science and Technology) [12] is a program focused on fostering innovation in accelerator science and technology, with a work package on innovative superconducting magnets that aims to develop HTS technology for particle therapy gantry and synchrotron magnets, aligning it with the sustainable technology goals of SEEIIST.

3.1. Main Features of the HITRIplus Demonstrator.

The HITRIplus collaboration's WP8 aims to review possible solutions for the design of superconducting magnets for gantry and synchrotron in ion therapy (beam rigidity of 6.6 Tm). The collaboration will design, manufacture, and test a prototype magnet using Nb-Ti wound as CCT, conduction cooled with impregnation, with a central field of 4 T, a free aperture of 80 mm, and a maximum ramp rate target of 0.4 T/s [15, 16]. The most critical challenge is that the magnet must be curved with a very small bending radius of 1.65 m and have a field quality suitable for accelerators or beam lines.

The design of the demonstrator [15] is based on a rope cable conductor with a proposed 2×8 ropes-in-groove layout, made of 6 low-loss Nb-Ti strands [10] and a central core of copper. Each rope has a current of about 1.5 kA, a good value to avoid excessive current leads loss. The CCT path has been optimized using an algorithm that returns the optimal current density distribution and 3D winding paths [17]. A yoke optimization has also been proposed using geometrical alterations of the yoke in the form of holes and notches to improve the field quality (Fig. 3, left). The preliminary mechanical design study has been completed, including FEM simulations to verify magnet behavior during cooldown and energization, the manufacturing procedure for curved CCT formers, and a complete assembly procedure [18].

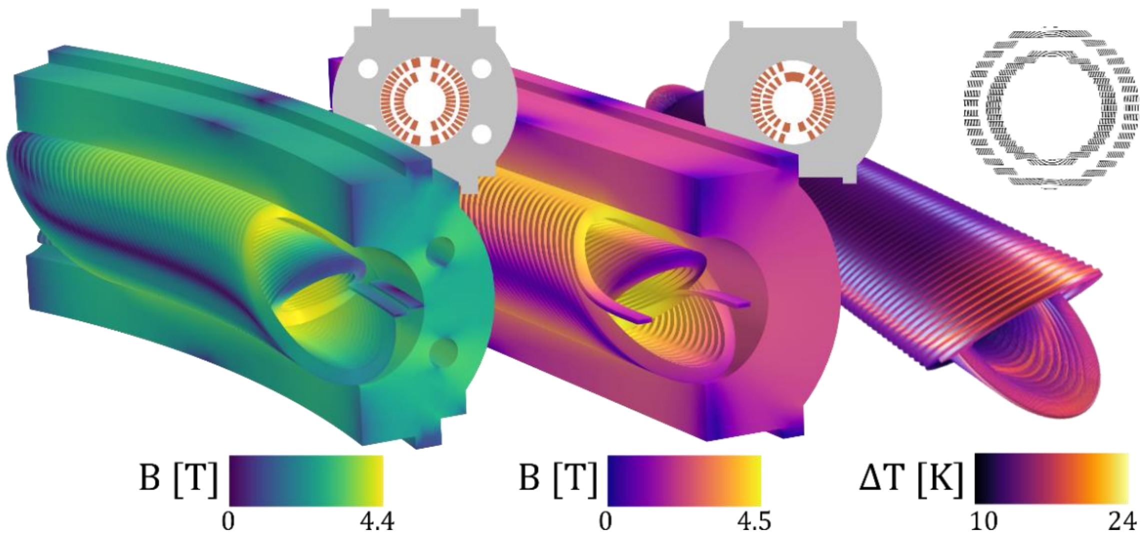

Figure 3. Cross sections and 3D layouts of the magnetic field maps of the curved CCT Nb-Ti HITRIplus (left), combined straight CCT Nb-Ti I.FAST (center), and temperature margins of the straight CCT based on HTS I.FAST (right).

3.2. Main Features of the I.FAST Demonstrators

The main goal of the IFAST WP8 is to advance HTS technology with CCT layout in collaboration with industry and institutes, with the final goal of manufacturing an HTS CCT demonstrator of 4 T at 20 K of operational temperature. A simpler magnet based on Nb-Ti will be manufactured first to learn, and it will be a combined function magnet with a superimposed quadrupolar component of 5 T/m. Both the I.FAST demonstrators will be straight co-sharing almost the same parameters of Table 1, except the curvature radius, and the operational temperature.

A preliminary design study of the straight combined-function CCT (Nb-Ti) magnet demonstrator (Fig. 3, centre) is presented in [19], achieving a target dipole field of 4 T and quadrupole field of 5 T/m at nominal current and 4.7 K temperature. The magnet has a load line margin of 28.7% @4.7 K and

33.4% @4.2 K, a critical temperature of 6.3 K with a temperature margin of 1.6 K, and a magnetic length of 0.73 m, figures that are similar to the curved pure dipole HITRIplus CCT. The iron yoke geometry serves as a collar, field contributor, and magnetic shield. The design study includes a mechanical analysis exploring materials such as aluminium-bronze 954 and PEEK GF30 for the formers, with stresses on both the formers and conductor remaining within limits. A preliminary protection study highlights larger time margins compared to high field magnets, with a rope of 6 Nb-Ti [10] + 1 copper strands selected as a baseline due to its 17% higher limit in terms of Quench Integral (QI). As well as for the curved CCT, the eddy currents induced in a metallic former can cause significant losses, particularly for bulk formers like aluminium-bronze-954 (13 W/m). The losses due to the conductor are about 1 W/m at 4 T (2 W/m at 0.45 T), presenting a thermal design challenge, as they will rely on cryocooler or He gas cooling.

The preliminary design of the CCT HTS demonstrator (Fig. 3, right) is based on REBCO tapes, and to avoid or minimize the hard-way bending, the Frenet-Serret frame was used in the CCT equations. Two design options are proposed, one using a cable with two tapes and the other with four tapes, and both reproduce a 4 T central field. The tapes, including copper stabilizer tapes, should be soldered together after winding. Both designs have a temperature margin of 10 K at an operating temperature of 20 K. The required thickness of copper stabilizer tapes is determined using an adiabatic quench analysis. Geometric field quality can be achieved by describing the radius of the coil using a Fourier series. The AC losses during operation are on average 50 W for both designs for a ramp 0-4 T and a rate of 0.4 T/s.

4. Conclusion and Discussion

The main design parameters for the magnet demonstrators of three programs (SIG, HITRIplus, and I.FAST) have been fixed to common values. The programs are quite complementary and should be able to lead us to an optimised decision for a final magnet prototype in two years. At present, the baseline is the cosθ design.

Various aspects of CCT and cosθ solutions are quite similar, with cosθ being slightly more efficient in terms of conductor quantity. However, cosθ requires a higher current, which results in increased power consumption in the current leads or a more complex winding with additional layers. On the other hand, the manufacturing of the CCT mandrels is not an industry standard and its feasibility has to be demonstrated, especially for the curved geometry.

References

[1] A. Degiovanni and U. Amaldi, “History of hadron therapy accelerators”, Physica Med., vol. 31, no. 4, pp. 322–332, 2015. doi:10.1016/j.ejmp.2015.03.002
[2] T. Haberer et al., “The Heidelberg ion therapy center”, Radiotherapy Oncol., vol. 73, pp. S186–S190, 2004. doi:10.1016/S0167-8140(04)80046-X
[3] Y. Iwata et al., “Design of a superconducting rotating gantry for heavy-ion therapy”, Phys. Rev. Spec. Top. Accel. Beams, vol. 15, no. 4, p. 044701, 2012. doi:10.1103/PhysRevSTAB.15.044701
[4] U. Amaldi et al., “SIGRUM- A superconducting ion gantry with Riboni’s unconventional mechanics”, CERN, Tech. Rep., 2021, https://cds.cern.ch/record/2766876
[5] L. Rossi et al., “Preliminary study of 4 T superconducting dipole for a light rotating gantry for ion-therapy”, IEEE Trans. Appl. Supercond., vol. 32, no. 6, p. 4400506, Sep. 2022. doi:10.1109/TASC.2022.3157663
[6] M. Karppinen et al., “Design of a Curved Superconducting Combined Function Bending Magnet Demonstrator for Hadron Therapy”, IEEE Trans. Appl. Supercond, vol. 32, no. 6, pp. 1-7, Sept. 2022. doi:10.1109/TASC.2023.3272576
[7] L. Rossi et al., “A European collaboration to investigate superconducting magnets for next generation heavy ion therapy”, IEEE Trans. Appl. Supercond., vol. 32, no. 4, pp. 1-7, Jun. 2022, p. 4400207. doi:10.1109/tasc.2022.3147433

[8] M. G. Pullia et al., “Explorative studies of an innovative superconducting gantry,” in Proc. IPAC'22, Bangkok, Thai-land, Jun. 2022, pp. 2966-2969. doi:10.18429/JACoW-IPAC2022-THPOMS012
[9] M. Prioli et al., "Design of a 4 T Curved Demonstrator Magnet for a Superconducting Ion Gantry," IEEE Trans. Appl. Supercond., vol. 33, no. 5, pp. 1-5, Aug. 2023. doi:10.1109/TASC.2023.3244523
[10] G. Volpini et al., “Low loss Nb-Ti superconducting ruther-ford cable manufacture for the SIS300 INFN model dipole,” IEEE Trans. Appl. Supercond., vol. 21, no. 3, pp. 3334–3337, Jun 2011. doi:10.1109/TASC.2010.2093112
[11] HITRIplus, “Heavy ion therapy research integration”, 2021, https://www.HITRIplus.eu/
[12] I.FAST, ”Innovation fostering in accelerator science and technology”, 2021, https://I.FAST-project.eu/
[13] G. Volpini et al., “AC losses measurement of the DIS-CORAP model dipole magnet for the SIS300 synchrotron at FAIR”, IEEE Trans. Appl. Supercond., vol. 24, no. 3, pp. 1-5, Jun. 2014. doi:10.1109/TASC.2013.2280733
[14] M. Sorbi et al., “Field quality and losses for the 4.5 T superconducting pulsed dipole of SIS300”, IEEE Trans. Appl. Supercond., vol. 18, no. 2, pp. 138–141, 2008.
[15] D. Barna et al., “Magnet Layout decision and engineering design report of the curved CCT dipole magnet demonstrator for the HITRIPlus project”, unpublished.
[16] E. De Matteis et al., “Straight and curved Canted Cosine Theta superconducting dipoles for ion therapy: comparison between various design options and technologies for ramp-ing operation”, in IEEE Trans. Appl. Supercond., vol. 33, no. 5, pp. 1-5, Aug. 2023. doi:10.1109/TASC.2023.3259330
[17] D. Veres et al., “A New Algorithm for Optimizing the Field Quality of Curved CCT Magnets”, IEEE Trans. Appl. Su-percond., vol. 32, no. 5, pp. 1-14, Aug. 2022. doi:10.1109/TASC.2022.3162389
[18] Gabriele Ceruti, “Preliminary Mechanical Design of a Super-conducting Magnet Canted-Cosine-Theta (CCT) for a New Gantry for Hadron Therapy”, Master Thesis, 2022. https://cds.cern.ch/record/2808359
[19] E. De Matteis et al., “Conceptual Design of combined CCT in LTS”, Zenodo, Feb. 2022. doi:10.5281/zenodo.6389851