A European Collaboration to Investigate Superconducting Magnets for Next Generation Heavy Ion Therapy

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A European collaboration to investigate Superconducting Magnets for Next Generation Heavy Ion Therapy

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***Abstract*— Next generation ion therapy magnets both for gantry and for accelerator (synchrotron) are under investigation in a recently launched European collaboration that, in the frame of the European H2020 HITRI*plus* and I.FAST programmes, has obtained some funding for work packages on superconducting magnets. Design and technology of superconducting magnets will be developed for ion therapy synchrotron and -especially- gantry, taking as reference beams of 430 MeV/nucleon ions (C-ions) with 10^{10} ions/pulse. The magnets are about 60-90 mm diameter, 4 to 5 T *peak* field with a field change of about 0.3 T/s and good field quality. The paper will illustrate the organization of the collaboration and the technical program. Various superconductor options (LTS, MgB_2 or HTS) and different magnet shapes, like classical CosTheta or innovative Canted CosTheta (CCT), with curved multifunction (dipole and quadrupole), are under evaluation, CCT being the baseline. These studies should provide design inputs for a new superconducting gantry design for existing facilities and, on a longer time scale, for a brand-new hadron therapy centre to be placed in the South East Europe (SEEIIST project).**

***Index Terms*—Superconducting magnets, Accelerator magnets, Particle beam handling, Particle therapy, Medical accelerators.**

I. INTRODUCTION

THE use of particles accelerated at a few hundreds of MeV per mass unit for cancer therapy is now an established medical technique [1]. The goal of particle therapy is not to replace conventional X-ray RT (radio therapy) that requires a smaller and less expensive infrastructure, but to provide the radiation oncologists with an alternative tool for the fraction of tumours that are not curable with conventional X-rays or have better survival rates or lower recurrences when treated with particle beams. Out of 24 particle therapy centers in Europe only four of them employ heavy ions (Carbon ions), all the other centers are employing only proton beams for treatment. In the world there are 12 centers using ions, out of the total 105 particle centers. Thanks to their higher energy deposition per unit length, heavy ions like Carbon are effective for some tumours resistant to X-rays and protons. Despite this, use of ions is so far limited by the size and cost of the required infrastructure.

Typically, cost and size maybe up to three times larger for the accelerator and beam line of a therapy center using both protons and ions than for a proton-only center. In addition, almost all proton centers are equipped with a gantry for enabling multiple directions of beam delivery, strongly enhancing the treatment effectiveness, sparing the surrounding healthy tissues. On the contrary very few ion centers are equipped with a gantry. The first, and unique in Europe, has been the pioneering center of HIT (Heidelberg Ion Therapy center) [2]. Based on classical resistive magnets, it has a length of 26 m and a weight of about 600 tons (rotatable part) and entered into operation in 2012. A huge step has been done at HIMAC (Heavy Ion Medical Accelerator in Chiba) of NIRS (National Institute of Radiation Science), designing and manufacturing a gantry based on superconducting (SC) magnets [3]. This has allowed the Japanese

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center to reduce the size and weight by about a factor 2. This HIMAC SC gantry is operative since 2018 and is so far the reference for SC ion gantry.

A further reduction of size and weight, and of the cost, would certainly enable a wider diffusion of ion gantries, thus contributing to better coverage of the territory by ion therapy centers.

II. THE EUROPEAN INITIATIVES FOR SUPERCONDUCTING MAGNET GANTRY AND SYNCHROTRON

In this context in Europe, after many paper studies on SC gantries, a few initiatives are taking ground.

An initiative generated by TERA (Foundation for oncological hadron therapy) and CERN culminated with two designs: one is a very light (~50 tons) rotatable gantry based on costheta magnets (called SIGRUM [4], [5]) and the other is based on a novel concept of a static toroidal SC magnet, called GaToroid [6]. After a couple of years of pre-study, the collaboration (led by CERN and extended to CNAO [7], MedAustron [8] and INFN), has recently favored as first step the detailed design and construction of the rotatable SIGRUM gantry. Both SIGRUM and GaToroid are based on Nb-Ti superconductor.

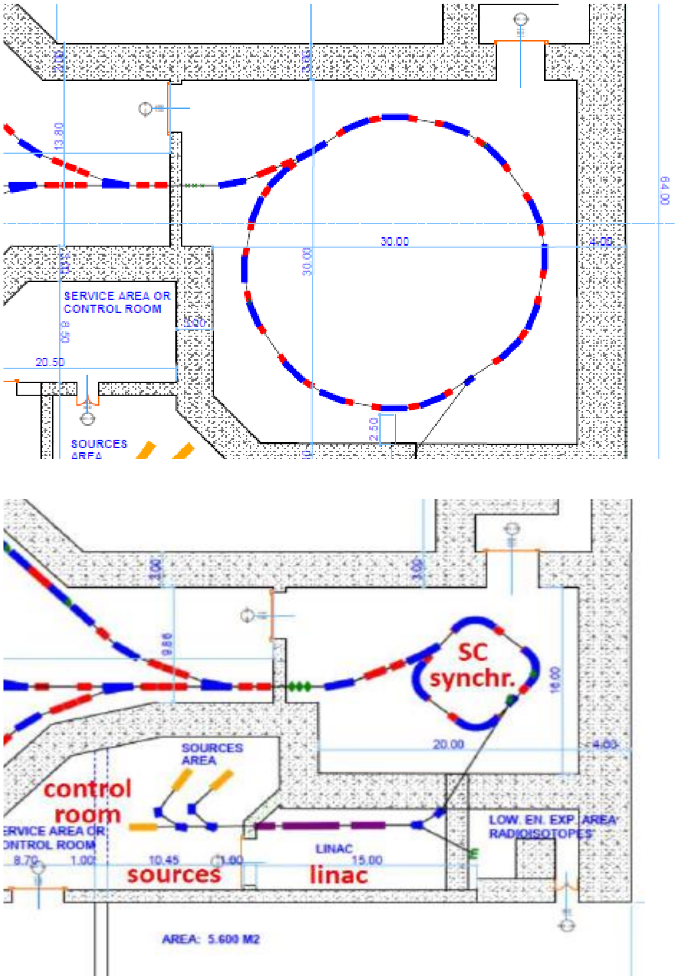

Fig. 1. Comparison between footprint of the accelerator hall in case of standard resistive magnet synchrotron (top picture) and in case of using SC magnets (bottom picture).

A second parallel initiative is the proposal of a new research infrastructure: the SEEIIST (South East European International Institute for Sustainable Technology) [9]. Supported by the European Commission (EC) and based in the Balkan area with also the scope of favoring the scientific development and collaboration among countries of that region, this new research infrastructure will focus on cancer therapy and biomedical research with protons and heavy ions. It features the use of an advanced ion gantry based on Nb-Ti SC magnets. The accelerator is at the moment designed as classical solution based on resistive magnets, however the study of an alternative SC magnet synchrotron is part of the design study, with the ultimate goal to reduce the accelerator footprint by more than 50%.

In Fig. 1 the sketch of the accelerator hall is shown in case of the baseline resistive synchrotron and in case of a SC synchrotron [10]. The SC accelerator consists of only four 90 degree dipoles of field of 3.5 T: however, one has to note that the accelerator hall is maybe one quarter of the whole infrastructure. The field is not high; however, the magnet has to withstand a field ramp of 1 T/s, at least, while keeping losses as low as possible.

In Fig. 2 a preliminary conceptual sketch of a light rotatable gantry presented in [4, Fig. 6] is shown. It is based on a design employing a simple and light mechanical structure and on 90 degree bending "tube" dipoles, the light blue curved tubes in the sketch. The dipole magnets, of the CCT type (see section III for explanation) contain also a alternating gradient winding for providing focussing in a compact way. The tubular dipole can be similar to the synchrotron one. However, the required field for the gantry is, possibly, in the 4-5 T range, while the ramp rate can be limited to about 0.3 T/s. In case of the gantry, due to rotation, use of dry, cryocooled magnets is envisaged. This solution is attractive also for the synchrotron, to avoid using liquid helium systems: however, the higher field ramp rate, which entails higher losses, may require liquid helium as coolant. Since the magnets are posed on ground this solution is certainly possible.

Given the growing interested in SC magnets, a few European Institutes have formed a collaboration and applied to the EC Horizon2020 framework programme for a partial funding of an

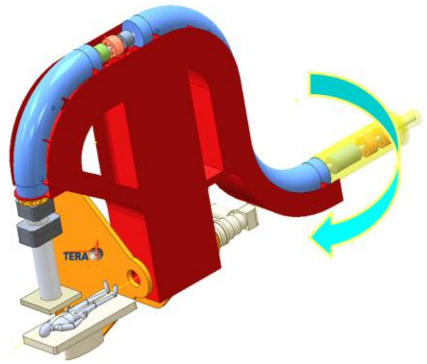

Fig. 2.Sketch of compact ion gantry based on 3 SC CCT 90° magnets. Courtesy of TERA foundation, [4].

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R&D and design program on innovative SC magnets for particle therapy. After an unsuccessful attempt in 2019 (H2020-HITRI application) two applications of Spring 2020 were approved in November 2020 and have just kicked off, after signature of the research contract in Spring 2021.

III. SUPERCONDUCTING MAGNETS WORKPACKAGE IN H2020-HITRIPLUS AND IFAST

A. *HITRIplus – WP8*

The Heavy Ion Therapy Research Integration *plus* (HITRI*plus*) [11] is a collaboration consisting of 22 institutes (4 centers for ion treatment, 10 research institutes, 5 universities and 3 small-medium enterprises) coordinated by CNAO, the National Center for Oncological Hadron therapy in Pavia, Italy. The collaboration has been awarded a €5M grant under EC-H2020. The grant started effectively on 1st April 2021 and is complemented by further resources provided by the member institutes, called matching funds. Matching funds strongly vary among the 13 work packages (WP) into which the program is divided. The program, to be carried out in four years has the goal, among others, of strengthening the position of Europe in the treatment of cancer with beams of ions, ranging from helium to carbon and to heavier ions. In this an explicit goal of the project is the development of novel technologies to improve the accelerators and their ancillary systems that provide particle beams for clinical therapy and for accelerator or biomedical studies. These technologies will improve the existing facilities like, for example, the study of a SC magnet gantry for CNAO and MedAustron but will also be the foundation of a next generation European design for ion therapy facilities [12] that, as SEEIIST (or any other new initiative in the EU), envisages the use of SC magnets both for gantry and maybe for accelerators, this last being a moderately fast ramped synchrotron. Therefore, inside the HITRI*plus* collaboration a WP is dedicated to SC magnets: WP8 – Superconducting Magnet Design, with the primary scope to explore a novel, robust, cost-effective magnet design for a light rotatable gantry and for the accelerating synchrotron.

1) *Collaboration Members*

The collaboration of WP8 includes seven research Institutes and one SME:

- INFN (divisions of Genova and Milano-LASA, It)
- CEA (Saclay, Fr)
- CERN, (Geneva, Ch, international organization)
- CIEMAT (Madrid, Sp)
- PSI (Villigen, Ch)
- Uppsala University-Freia laboratory (Se)
- Wigner Research Centre for Physics (Budapest, Hu)
- Sentronis, a Serbian company associated via SEEIIST

CNAO and SEEIST participate in the work of WP8, that is strongly linked with WP7-Accelerator design, led by CERN.

2) *Objectives of HITRIplus WP8*

The first objective of the HITRIplus WP8 is to perform a wide review of the possible solutions for the gantry and synchrotron, assessing the use of various types of superconductor and magnet layouts. Then the collaboration is committed to designing, manufacturing and testing one magnet demonstrator. We plan to assess various options among conductors: LTS (Nb-Ti and Nb_3Sn), HTS (REBCO, Bi-2212), MgB_2 and among coil layouts: CosineTheta (CT), Canted Cosine Theta (CCT) [13] or race-track (RT). However, for design and construction of a prototype the collaboration has chosen as provisional baseline Nb-Ti wound as CCT, conduction cooled with impregnation.

The main technical characteristics of the magnet will be discussed in detail in the dedicated section. Nevertheless, we recall here the main characteristics: a central field B_0 of 4 to 5 T, a free aperture ranging from 60 to 90 mm. The demonstrator will have a length of 500 mm of uniform field. The magnets must have a field quality (FQ) suitable for accelerators or at least for beam lines, i.e. with uniformity in the good field region, ~2/3 of the aperture, ranging from 10^{-3} to 10^{-4} of the main field (in technical language, 10 units for beam lines and 1 unit for accelerator). Another challenge is the ramp rate ranging from 0.3 T/s for the gantry to 1 T/s for the synchrotron. Finally, the most critical challenge is that the magnet must be curved [14] with a very small bending radius, dictated by the 430 MeV/nucleon of the fully stripped carbon ions which have a beam rigidity: $B\rho = 6.6$ Tm. Therefore, the bending radius ranges from 1.3 m to 1.6 m according to the field level that will be chosen. We estimate that such a small bending radius is maybe the most difficult parameter to demonstrate in this project.

The choice of Nb-Ti is based on the fact that in the past an INFN team has designed and manufactured a dipole that reached 0.7 T/m with 4.5 T, for the FAIR project [15]. However, that magnet was designed for operating at 1 T/s in forced flow supercritical helium and actually reached the 0.7 T/m in the test carried out in a liquid helium (LHe) vertical bath. For HITRI*plus* the thermal design will be more critical given the indirect cooling.

3) *Structure, detailed program and budget*

The WP8 program is coordinated by INFN and is structured into 5 tasks (in parenthesis the task leading institutes)

1) Task 8.1 (INFN and CEA) includes, beside coordination, the assessment of state-of-the-art, and has the goal to provide a solid list of magnet parameters for the design, trying to serve as much as possible both gantry and synchrotron options, while privileging the gantry.
2) Task 8.2 (CEA and INFN) has the goal of carrying out a comparative study among various designs and types of superconductors, to understand the pros and cons of each design and when various solutions might be convenient in the wide parameter space. This study will eventually validate (or invalidate) the preliminary choice of Nb-Ti CCT, for our parameters (given by Task 8.1). In order to consistently compare various options we use this common set of parameters: $B_0 = 4.5$ T (pure dipole field) at 80% of the critical surface on the load line (short sample limit), $\varnothing_{coil} = 75$ mm, straight shape with $L_{magnetic} = 800$ mm. $T_{op} = 5$ K, 10 K, 20 K. Considerations on scalability to 5+ T, on possibility to superimpose a 5 T/m quadrupole gradient, either as combined function winding or with nested configuration, as well as on easiness of

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bending the magnets at R of 1.5 m will be also part of the assessment. The straight shape and the other parameters are only for this preliminary comparison among options: the demonstrator will actually be a curved dipole.

3) Task 8.3 (Wigner RCP and CIEMAT) has the job of delivering a consistent design of the curved demonstrator, according to the chosen solution (Nb-Ti CCT at present). The design will include a set of manufacturing drawings and an estimation of the cost.
4) Task 8.4 (CIEMAT and INFN) covers the construction of the demonstrator and proper qualification for test. The test itself is part of the program without being a formal deliverable (since it is subject to availability of the test stations, at CERN or at Freia (Uppsala University), therefore it may be carried out after the formal end of HITRI*plus*.

The budget provided by the EU is limited to 465 k€ in total over the four years. However, the budget is enhanced by contribution from each partner, called matching funds, typically of the same order as the EU contribution, so the program has a nominal total value of 1070 k€. All previous figures include 25% flat rate overhead.

B. IFAST -WP8

IFAST (Innovation Fostering in Accelerator Science and Technology) [16] is a vast program consisting of 48 members, mostly being Research Institutes and Universities active in the field of particle accelerators. It is the omnibus program continuing the tradition of FP7-CARE, FP7-Eucard, FP7-Eucard2 and H2020-ARIES programs [17], [18]. Like its predecessor programs, IFAST features a work package on magnets, called WP8 - Innovative Superconducting Magnets. It has been proposed by the same research institutes of HITRIplus WP8 (the same WP# is a coincidence) and has the scope of studying CCT magnet design in HTS together with industry, for particle therapy with hadrons (namely heavy ions). While there are strong similarities with the goals of HITRI*plus* WP8, like the magnet size and field level, IFAST concentrates the effort on HTS technology development rather than on "robust" magnet design. We are convinced that HTS has great potential to become the workhorse for particle therapy gantry and synchrotron magnets. However, the technology is not yet mature enough, at least in Europe, to design and successfully operate a gantry or a synchrotron in the next years. IFAST-WP8 has the goal to bring the HTS CCT technology to maturity to allow for a later design of a full HTS system. If successful and if the time scale fits, HTS technology operating at higher temperature than 5 K with consequent energy saving, is well-aligned with the main goals of SEEIIST (the "ST" stands for "Sustainable Technologies").

1) Collaboration members

The collaboration of WP8 includes eight academic institutes and three companies:

- INFN (divisions of Genova and Milano-LASA, It)
- CEA (Saclay, Fr)
- CERN, (Geneva, Ch, international organization)
- CIEMAT (Madrid, Es)
- PSI (Villigen, Ch)
- University of Geneva
- Uppsala University-Freia laboratory (Se)
- Wigner Research Centre for Physics (Budapest, Hu)
- Bilfinger Noell Gmbh, BNG, (Wurzburg, De)
- Elytt Energy SL (Artea, Es)
- Scanditronix Magnet AG (Vislanda, Se)

The presence of three companies, BNG, Elytt and Scanditronix, enables us to meet one of the main goals of IFAST: favoring the technology exchange between Academia and Industry. The group of research institutes being the same as that in HITRI*plus* WP8, with the addition of the University of Geneva, favors maximization of the synergy between the two programs.

2) Objectives, structures and budget of IFAST-WP8

As mentioned above the main objective of the WP is to advance HTS technology with CCT layout in a collaborative way between institutes and industry. To this end the final goal is to manufacture a HTS CCT demonstrator of about 5 T. However, this demonstrator will be preceded by a simpler magnet in LTS (most probably in Nb-Ti) to learn. Initially this first magnet had been foreseen to be curved. Since a curved Nb-Ti is in the scope of HITRI*plus* WP8 (this was not known at the time of IFAST application), we have decided to manufacture a combined function magnet as a first simpler demonstrator. Superimposed to the main dipole field of 4-5 T there will be a quadrupolar component of 5-10 T/m which will yield about 0.5-1 T additional peak field. Whether the combined function is better to be achieved by nested coils or by combined winding (this solution being favorite) is still under discussion. The task structure and details of the program, coordinated by INFN, is detailed in the following:

1) Task 8.1 (INFN and CEA). Beside the coordination of WP8, this task will organize a European Strategy Group on HTS, a permanent body chaired by CERN that has to coordinate the R&D on HTS for accelerator magnets for various applications, favoring synergies and collaborative efforts also for different applications, like medical ones and high-energy colliders.
2) Task 8.2 (INFN, CERN). This task takes care of the preliminary engineering design of the first demonstrator, the combined function magnet. Here we want to study, very much like in HITRI*plus*, the Nb-Ti magnet. However, we will also evaluate if low losses Nb_3Sn can have important advantages vs Nb-Ti such as to offset the higher cost of the A15 compound.
3) Task 8.3 (CEA, INFN). Here the institutes will design a HTS CCT selecting the most suitable conductor among various possibilities. At present REBCO seems a better choice than Bi-2212 or Bi-2223, for its availability and the experience on previous EU programs (Eucard and Eucard2) [17]-[19]. Use of controlled-insulation (or metal-as-insulator) technology will be explored to understand if it is compatible with stringent accelerator and beam line requirements.

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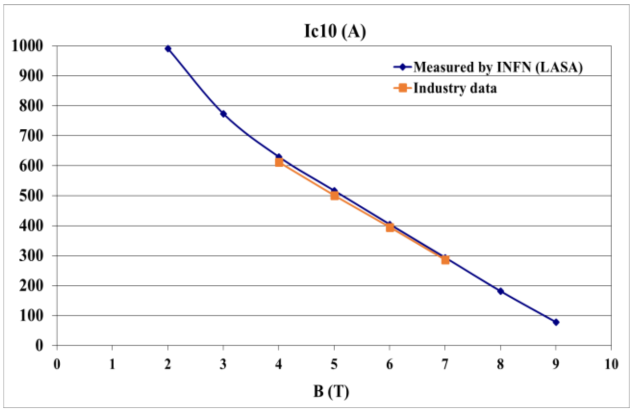

Fig. 3. Critical current measurement with electrical field criterion at 10 muV/m @ 4.22 K of the DISCORAP

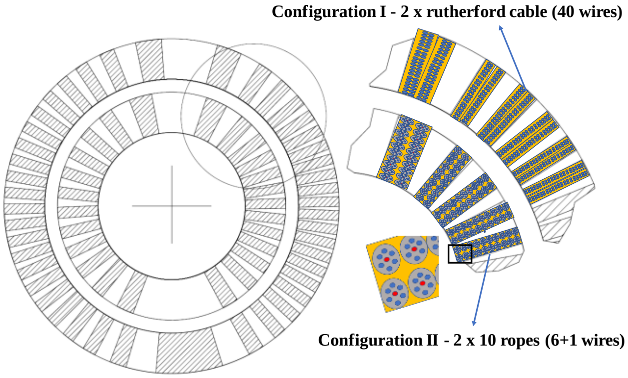

Fig. 4. Straight Combined CCT cross section with a representation of the two preliminary conductor layouts: configuration I, two Rutherford cables with 40 wires each, and configuration II, two times 10 ropes with 6+1 wires.

4) Task 8.4 (BNG and Scanditronix). This task is led by the two companies that will take care of manufacturing the first CCT demonstrator, the LTS combined function CCT. The research institutes, beside design and technology support, will provide the conductor.

5) Task 8.5 (Elytt and BNG). This task covers the construction of the main deliverable, the HTS CCT magnet demonstrator. The two companies leading the task will take care of the actual construction and qualification, while the institutes, besides providing the design and the HTS conductor, will take care of the final test at cold.

The EU provides about 700 k€, in total over the four years, and the total budget, with matching funds from the participants, amounts to 1250 k€, including 25% flat rate overhead.

IV. PRELIMINARY WORK

The study of HITRI*plus*, that has started on 1st April 2021 and will end by March 2024, logically precedes the one of IFAST, that has begun on 1st of May 2021 and will end in April 2025. HITRI*plus* aims also at providing useful input to the final design of SIGRUM gantry, which should be frozen in the next 2-3 years.

A. Conductor and magnet design

We have selected the Nb-Ti wire that will be used for the conductor of the HITRI*plus* demonstrator and of the first IFAST demonstrator. It is a special low loss wire with fine filaments in a Cu-Mn matrix, with stabilizing copper surrounding the Nb-Ti/Cu-Mn core, manufactured for the cited Discorap project [15]. In table I the main characteristics and in Fig. 3 the Ic vs field curve are reported. The corresponding critical current density, J_c, is about 2300 A/mm^2 at 5 T reference field. Though about 20% less than LHC wires J_c, it is a good value for low losses small filament Nb-Ti/Cu composite wires.

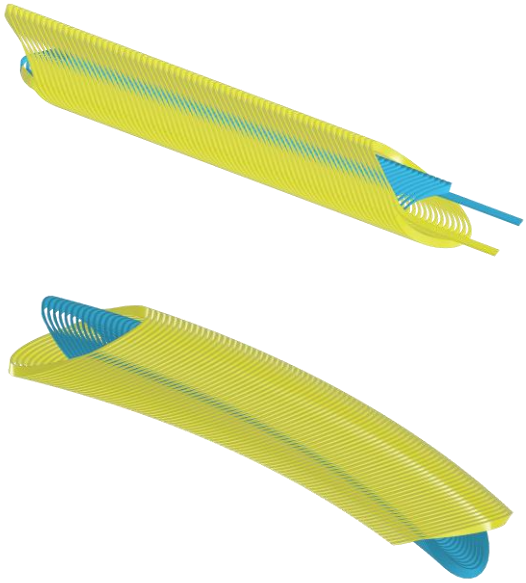

Fig. 5. First sketches of a straight and a curved version of the CCT conductors.

TABLE I
NBTI STRAND FEATURES

Features	Value	Meas. unit
Diameter	0.821	mm
Cu/NoCu	1.36	-
Twist length	6.6	mm
Filament dia.	3.3	µm
J_c (5T @ 4.2 K)	2296	A/mm^2
I_c (5T @ 4.2 K)	516	A
RRR	135	-
n	>30	-

We have so far examined two preliminary designs (Fig. 4):

a) a “high current” solution, where two rectangular insulated Rutherford cables of 40 wires are wound in parallel. By connecting them in series we obtain a high field limiting the feeding to about 12480 A, a considerable figure, that can be handled only by using He gas for the indirect cooling of the coil.

b) a “low current” version, where the grooves are filled with twenty round ropes (2 times ten), of classical 6+1 topology. Each rope is insulated and connected in series to keep the amperage low. In this case the feeding current is 1536 A, however multiple electrical joints have to be integrated in the design.

In table II the main characteristics are reported for the two solutions, while in Fig. 5 the first sketch of a straight and a curved version of the CCT conductors is reported. In Fig. 6 the

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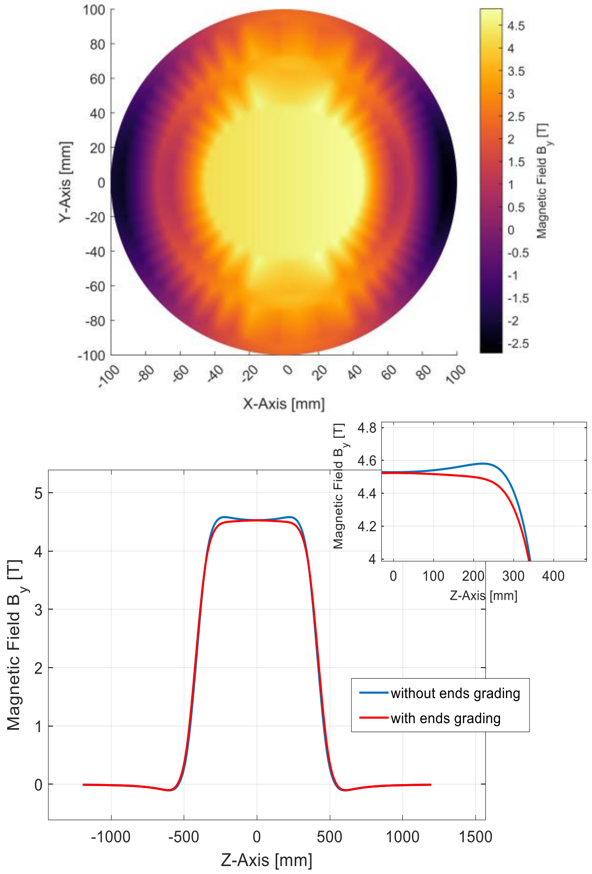

Fig. 6. Field map and profile of the By in the cross section (at z=0) and along z-axis (blue line is without ends grading, and red one with ends grading).

field map is depicted together with the field profile along the axis. The field profile is provided for a simple solution, where the field has a peak at the entrance/exit of the magnets and for a solution where the coil ends have a continuous optimization of the distance between turn (variable thickness of the ribs at the pole position, i.e. ends grading), which avoids that the field increases above the one of the magnet center. We stress that at this stage we are carrying out a design without iron. This is because we use this design to compare with various superconductors and different layouts, as mentioned above. Once the iron yoke is taken into account, in the final design, the amount of superconductor can be decreased by 20-25%. In principle cold or warm iron yoke layout can be selected, with various pros and cons that will be properly quantified.

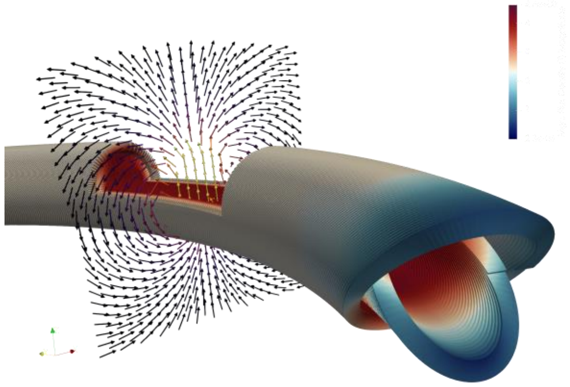

Fig. 7. CCT curved dipole with sketch of field lines (in arrows form).

The stress analysis is ongoing. The preliminary results show a transverse pressure with respect to the conductor direction on the rib edge of about 9 MPa at maximum magnetic field. The relative deformation is of a few tens of microns considering an aluminum former.

TABLE II
CCT CHARACTERISTICS:
(I) 2 X RUTHERFORD CABLES AND (II) 2 X 10 ROPES

Parameters	Value		Unit
Configurations	I	II	
Bore Diameter	75		mm
Groove Width	4	5	mm
Groove Height	20	25	mm
Spar Thickness	8		mm
Ribs Min. Thickness	1.25		mm
Number Turns	78	66	-
Number of Strands	80 (2x40)	120 (6x2x10)	-
Current per cable	12480	1536	A
Magnetic Length	807	811	mm
By @ z = 0	4.50	4.53	T
Short sample fraction of loadline	82.7	77.8	%
Length of conductor	8500	11500	m

B. *Field quality for curved magnets*

The traditional multipole analysis has a questionable justification for accelerator magnets with a strong curvature, since cylindrical multipoles are not solutions of Maxwell's equations in a curved coordinate system. For the characterization of field quality and the optimization of winding geometry, the usage of field derivatives $\partial^n By/\partial x^n$ has been adopted, which fully characterize the field around the nominal trajectory for fields with mid-plane symmetry [20], in-line with the practice of beam dynamics simulations. For the canted cosine theta topology an optimization framework (based on a semi-analytical approach using toroidal harmonics, and the simulation software RAT [21]) has been developed which can determine the ideal winding geometry to obtain a prescribed set of field derivatives inside the translation-invariant body of the magnet, like the solution shown in Fig. 7. Evaluation of the effect of the fringe fields of the magnet, and eventual feedback into the optimization of the winding geometry will be worked out in the next step.

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