The 16 T Dipole Development Program for FCC

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***Abstract*—A key challenge for a future circular collider (FCC) with centre-of-mass energy of 100 TeV and a circumference in the range of 100 km is the development of high-field superconducting accelerator magnets, capable of providing a 16 T dipolar field of accelerator quality in a 50 mm aperture. This paper summarizes the strategy and actions being undertaken in the framework of the FCC 16 T Magnet Technology Program and the Work Package 5 of the EuroCirCol.**

***Index Terms*—FCC, Nb_3Sn, superconducting, 16 T.**

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I. Introduction

THE FCC study was approved in 2013 by the CERN Council [1] within the European Strategy for Particle Physics. The study is based on the use of 16 T bending magnets, with an aperture of 50 mm, for which a conceptual design has to be ready to be integrated in the FCC Conceptual Design Report in 2018. Such a field level is almost twice that of the Nb-Ti magnets presently installed in the LHC. It is also more than 4 T higher than the field in the Nb_3Sn magnets being developed for the High Luminosity LHC (HL-LHC) [2]–[3], which will be the first high field Nb_3Sn magnets ever operating in a particle accelerator. A higher field amplitude (13 T operational, with a potential of exceeding 15 T at short sample) Nb_3Sn dipole magnet presently under development in the framework of the FP7 European project EuCARD is Fresca2 [4]–[5]: the magnet, which also features a large 100 mm bore, is planned to be assembled by the end of 2016.

The idea of developing magnets operating at about twice the field than the one of the LHC has been explored already as a mean to increase the energy of the LHC itself: the so called High Energy LHC (HE-LHC) [6]. This still remains an option which may largely profit of the developments performed in the framework of the FCC program.

The highest field amplitudes in a dipole configuration with accelerator aperture have been achieved so far at LBNL: the D20 [7] achieved 13.5 T at 1.9 K in a 50 mm bore, and the HD2c [8] achieved 13.8 T at 4.3 K in a 36 mm bore.

A 16 T field in a dipole configuration was achieved till now on two short Nb_3Sn laboratory models [9]–[10] at LBNL and, later, at CERN. These models are however very different from an accelerator magnet, featuring no free aperture and having certain critical features (like magnet protection) not directly extendable to a long magnet. Furthermore, for the FCC magnets 16 T have to be achieved as operational field and not as the maximum field achieved on a test bench.

A common feature of all Nb_3Sn models produced so far is that they show long training especially when operated at 1.9 K. It is not clear if such behavior is an intrinsic limitation of the combination between the technology, imposing impregnated coils, and the large stresses due to the high fields, or if the observed performance can be largely improved with the use of new materials, design concepts and assembly techniques.

Furthermore, as most of the present experience comes from the manufacture and test of short or very short models, it is difficult to conclude if this performance is limited in the regular magnet section or it is mostly due to the transitions and discontinuities around the magnet extremities.

The 16 T dipole program for the FCC has been set to progressively cover most of the aspects required to prepare the development of high field Nb_3Sn magnets for a high energy circular collider, from the enhancement of the conductor performance to the design, manufacture and test of demonstrator magnets.

This paper covers the two active programs at this stage, namely the 16 T Magnets Technology Program established at CERN and the WP5 of the European Program EuroCirCol.

II. 16 T Magnets Technology Program

The 16 T Magnets Technology Program has been established at CERN in July 2015 and is organized in five tasks: strand development and procurement, wound conductor program, Enhanced Racetrack Model Coil (ERMC), Racetrack Model Magnets (RMM), and Demonstrators.

The first part of the program covers the period July 2015-June 2019 and is focused on:

1) improving the state of the art conductor performance with respect to the one specified for the HI-LUMI project [11], in particular to increase the critical current density (J_c) towards 1500 A/mm^2 at 16 T and 4.2 K;
2) studying the processes governing the conductor performance in a magnet through a tailored "wound conductor program";
3) demonstrating the field reach, and developing the basic magnet technology (grading and splicing, instrumentation) with ERMC models;
4) exploring and optimizing the performance (including training and field quality) of a representative magnet regular section with RMM models;
5) engineer, manufacture and test short model magnets representative of accelerator dipoles, as a result WP5 of EuroCirCol, and in collaboration with institutional partners.

It is planned to test a first ERMC during the year 2017 and a first RMM during the year 2018. Winding of a first demonstrator magnet, ideally developed as a result of an extended EuroCirCol, should start in 2019.

A. Strand development and procurement

This activity is composed of a program focusing on the industrial development, material analysis and qualification of Nb_3Sn conductor. Currently, the main technical target is to achieve a critical current density of $J_c \geq 1500\ \mathrm{A/mm^2}$ in the superconductor at 16 T and 4.2 K (wire diameter about 1 mm, Cu/Non-Cu ratio 1, and sub-elements/filament diameter about 50 μm). The main commercial target is to achieve a cost of 5 EUR/kA•m at 16 T and 4.2 K [12]. These two targets are intra-linked to each other, by increasing the critical current density the required amount of conductor is reduced and the magnet becomes more efficient and compact, which further reduces its cost. Therefore, first the required technology will be developed with numerous industrial partners world-wide, for the two different available technology routes: Internal-Tin and Powder-In-Tube. To this end contractual agreements are currently negotiated to produce small quantities of conductor meeting the target specifications. The contracts will span over a period of 4 years from 2016–2020. The development in industry will be accompanied with material analysis and qualification of Nb_3Sn conductor within the technology companion program. Within the WP5 of EuroCirCol a dedicated program to understand the stress dependencies of the different conductor varieties is on-going. Moreover, the main cost drivers for the wire production will be identified and a detailed study on the cost of Nb_3Sn conductor will be provided to guide the magnet designers in their design choices.

For the Enhanced Racetrack Model Coil (ERMC) and the Racetrack Model Magnet (RMM) state-of-the-art HL-LHC Nb_3Sn conductor will be procured and cabled.

B. Wound conductor

This activity is developed to study the characteristics and performance of the conductor once wound, thermally treated and impregnated, and is developed in four directions. The first study concerns the *characterization of cable windability*, by measuring and modeling the geometrical evolution of cables during coil winding, to possibly provide feedback for cabling and winding. A second activity concerns the *mechanical characterization of a cable stack*, by measuring and modeling the stress-strain distribution in a cable stack representative of a coil cross section. Presently, when a magnet is designed the coils are approximated by a number of blocks with uniform material characteristics. In reality, a coil is made of cabled strands, insulated and impregnated into a coil. The objective of the study is to understand if and how such a simplified model needs to be enhanced taking into account the composite structure of the coil. Another information needed to design a high field magnet is to quantify the maximum allowed stress and strain that a reacted and impregnated coil can sustain without degradation during magnet assembly. This will be performed by setting up a tailored experimental program to study the *coil degradation during magnet assembly.* Finally, the program intends to address the *study of the parameters affecting training performance*. An experimental set-up, composed of a U-shaped conductor, clamped in different conditions between an inner pole and an external elastic structure, will allow to explore training performance as a function of conductor properties, mechanical status of the conductor/coil and its interfaces (friction, gluing, contact boundaries, etc), elasto-plastic properties of the coil and of the structure, as well as the margins (field, current, load-line, enthalpy, etc).

C. Enhanced Racetrack Model Coil (ERMC)

The ERMC, a modified version of the RMC [13], is a dipole magnet composed of two superposed double-pancake flat racetrack coils with no, or very small bore. With respect to the RMC, the ERMC has more conductor and a stronger mechanical structure, with a potential of achieving a short sample dipole field intensity in a range between 18 T and 19 T depending on the conductor.

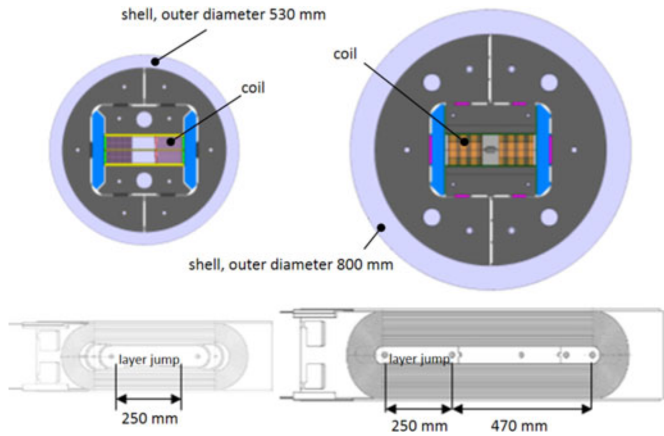

Fig. 1. Comparison between RMC (left) and ERMC (right) layouts

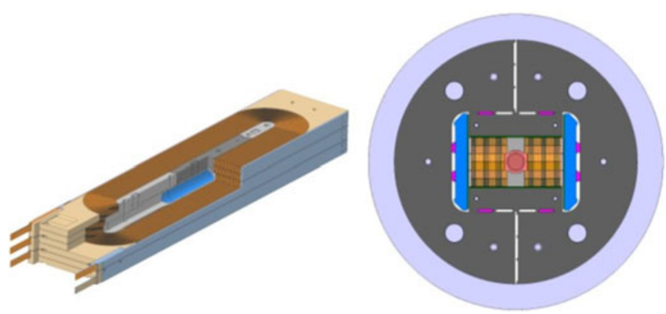

Fig. 2. RMM: 3D view of the coils and 2D cross section of the structure

In addition to the higher field intensity, the ERMC also features a much longer straight section (700 mm) than the RMC (which has a 300 mm long straight section, almost entirely occupied by the 250 mm-long layer jump transition). This opens the opportunity of studying the behavior of an almost "regular straight section", in particular the effect of different manufacturing techniques and materials (for example coil impregnation), assembly (for example interface to the coil pole) and coil loading conditions on the training performance. These differences are summarized in Fig. 1, where on the left side the RMC features a cross sectional diameter of 530 mm to be compared to 800 mm of the ERMC on the right side.

A description of the magnet design is given elsewhere [14].

D. Racetrack Model Magnet (RMM)

The RMM is a concept for studying the behavior of an accelerator magnet straight section, including field quality and relevant dynamic effects, using simple flat racetrack coils.

This is achieved, as shown in Fig. 2, by inserting, at the midplane location between two double pancake racetrack coils (in this case the same also used for the ERMC), one additional double pancake flat racetrack coil (middle coil).

The middle coil is wound around an insert forming a cavity representing the magnet bore, which for the RMM has been set to 50 mm in diameter as is the baseline for the FCC dipole magnets, in which the coil configuration and magnet structure has a potential of providing a short sample field of 18–19 T, depending on conductor characteristics.

The structure is the same as the one used for the ERMC, in which the different configurations (including magnet versions using graded coils) can be accommodated using appropriate spacers.

As the magnet is mainly designed to explore the performance of the straight section, a particular care has been devoted in designing the transitions of the layer jump and the end region in order to minimize the conductor field intensity at these locations. Though these are racetrack coils, the relevant methods and lessons learned will be useful in the design and manufacture of magnets using other coil geometries.

A description of the magnet design is given elsewhere [14].

E. Demonstrators

The technological development of the conductor and of the magnet technology will be exploited in the final stage of the program with the design, manufacture and test of one or several short demonstrator magnet models. Demonstrator models will be built within different frames in collaboration with partner institutes, in particular the ones engaged in WP5 of the EuroCirCol.

These magnets will be designed and built starting from the experience gained through the technological programs described so far, together with the design work matured in the framework of the EuroCirCol study. The program is presently under discussion and aims at testing between 2 and 4 demonstrator magnets within end 2022. These demonstrators will be single aperture short models, already implementing in the design the essential features and constraints required for a double aperture 14.3-m-long dipole magnet for the FCC, in particular concerning field quality, quench detection as well as magnet and circuit protection. A special attention will be devoted to the management of the transition regions and end parts of the coils, which are in most cases a primary cause of training.

III. WP5 OF EUROCIRCOL

EuroCirCol [15] is a conceptual design study for a post-LHC research infrastructure based on an energy-frontier 100 TeV circular hadron collider. The work package (WP5) for the high-field accelerator magnet design integrates results and ongoing activities from related projects on superconducting magnet research into a single, unified work to produce a 16 T accelerator magnet design with sufficient aperture and good field quality. The design shall be directly extendable to a double aperture 14.3-m-long magnet, in particular in terms of field quality, quench protection and circuit integration.

The objectives and deliverables of this study are to explore different design options for an accelerator dipole magnet in the range of 16 T; to produce conceptual designs for the most promising options; to develop a cost model for system optimization studies; to develop a preferred option into a baseline design based on performance merits and cost estimates; and finally to produce the engineering design of the selected baseline configuration, covering all electromagnetics, mechanical, thermal and operation aspects, including the manufacturing folder for a short model.

TABLE I
SALIENT BASELINE PARAMETER CONSTRAINTS FOR WP5 OF EUROCIRCOL

Parameter	Value
Reference magnet length	14.3 m
Free physical aperture	50 mm
Nominal bore field amplitude	16 T
Margin on the load-line @ 1.9 K	$>14\%$
Critical current density @ 1.9 K, 16 T	$2300\ \mathrm{A/mm^2}$
Cu/nonCu	>0.8
Hot spot temperature (@ 105% I_{nom})	<350 K
Strand diameter	<1.2 mm
Stress on the conductor @ 105% I_{nom}	<200 MPa
Voltage to ground (magnet only)	<1.2 kV
Total voltage to ground (incl. circuit)	<2.5 kV

A specific feature of this program is that different alternatives and design options are being considered with the same specification so that they can be evaluated and compared relatively to each other.

The study is performed through a collaboration of the following institutes: CEA, CERN, CIEMAT, INFN, KEK, University of Geneva, University of Tampere and University of Twente.

Since July 2015 three design options (common coil, cosinetheta and block-coils) have been explored with conservative parameters (margin on the load line 18%, number of strands in the cable limited to 40, Cu/nonCu $>$ 1.0, maximum strand diameter equal to 1.1 mm).

With these conditions, the resulting low current density in the high field conductor limits the current to around 10 kA in an optimized cross-section constituted by a large number of turns. This produces too high voltages in case of a quench, imposes a too dense fractioning of the powering circuits, and generates too large temperature gradients in case of quench. Furthermore, the 18% margin results in a non-cost efficient use of the conductor amount heavily affecting the real feasibility of the study.

In line with the recommendation of an external review performed in May 2016, it has been decided to modify the parameter space resulting in the reference Table I, which leads to what is believed to be a reasonable compromise between credible performance parameters and magnet cost and integration into a particle accelerator.

The present status of the program is detailed in several contributions at this conference: the three design options under consideration in [16] for the common coil, in [17] for the block coil, in [18] for the cosinetheta, the activity on quench studies in [19], and the work on the cost model in [20]. The three designs have been explored with both the initial parameter space and the modified one, using the same tools in particular for the quench analysis. The relevant studies confirm that the proposed new parameter space seems to represent an optimal compromise between performance and operational specifications, as well as the technical and financial feasibility.

In addition to the above activities, a specific task of the program, focused on the characterization of the mechanical parameters and electrical performance of conductors and cables under different types of mechanical loads, in particular transversal stress, is being initiated and yields synergy with the conductor program of the 16 T Magnets Technology Program.

It is planned to converge into a reference magnet design by spring 2017, to be thereafter developed to feed the FCC design report for a double aperture machine magnet. Furthermore, the interest of several national laboratories of being engaged in the development of demonstrator magnets may give the opportunity of developing the detailed design of more than one design option, ideally all options being potentially applicable to the FCC. This is why it has been decided that, until spring 2017, all the three designs under consideration will be further developed and optimized until a stage to constitute a base for a possible constructional design.

IV. CONCLUSION

Although the priorities are currently set for the High-Luminosity LHC Project, the activity devoted to the development of 16 T magnets for a future circular collider, and possibly for an energy upgrade of the LHC with higher field magnets, is now organized in a well-defined framework and has already provided interesting outcomes. In particular the work performed within the EuroCirCol collaboration has resulted in a set of specification parameters aiming at an optimal compromise between performance and cost, implemented in several magnet design variants. The program will allow to feed the FCC conceptual design report with a reference baseline design as well as provide a basis for the development of demonstrator magnets. Critical technologies (conductor development and characterization, internal splicing, impregnation, thermo-mechanical characterization of conductors, coils and magnet parts), manufacture and performance parameters (winding, coil loading, coil degradation, instrumentation, grading) are mainly being treated within the 16 T Magnets Technology Program. The combination of the two programs should allow to start winding a first demonstrator magnet in 2019.

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