Status of the 16 T Dipole Development Program for a Future Hadron Collider

D.Tommasini[1], D.Arbelaez[11], B.Auchmann[1], H.Bajas[1], M.Bajko[1], A.Ballarino[1], E.Barzi[10], G.Bellomo[2], M. Benedikt[1], S.Izquierdo Bermudez[1], B.Bordini[1], L.Bottura[1], L.Brower[11], M.Buzio[1], B.Caiffi[5], S.Caspi[11], M.Dhalle[3], M.Durante[4], G. de Rijk[1], P.Fabbricatore[5], S.Farinon[5], P.Ferracin[1], P.Gao[3], S.Gourlay[11], M.Juchno[11], V.Kashikhin[10], F.Lackner[1], C.Lorin[4], M.Marchevsky[11], V.Marinozzi[2], T.Martinez [6], J.Munilla[6], I.Novitski[10], T.Ogitsu[7], R.Ortwein[1], J.Perez[1], C.Petrone[1], S.Prestemon[11], M.Prioli[1], J.M.Rifflet[4], E.Rochepault[1], S.Russenschuck[1], T.Salmi[8], F.Savary[1], D.Schoerling[1], M.Segreti[4], C.Senatore[9], M.Sorbi[2], A.Stenvall[8], E.Todesco[1], F.Toral[6], A.P.Verweij[1], S.Wessel[3], F.Wolf[1], A.V.Zlobin[10]

***Abstract*—A next step of energy increase of hadron colliders beyond the LHC requires high-field superconducting magnets capable of providing a dipolar field in the range of 16 T in a 50 mm aperture with accelerator quality. These characteristics could meet the requirements for an upgrade of the LHC to twice the present beam energy (HE-LHC) or for a 100 TeV centre of mass energy Future Circular Collider (FCC). This paper summarizes the activities and plans for the development of these magnets, in particular within the 16 T Magnet Technology Program, the WP5 of the EuroCirCol, and the US Magnet Development Program.**

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

I. Introduction

A future Circular Collider (FCC) [1], or an energy upgrade of the LHC (HE-LHC) [2], would require bending magnets operating at up to 16 T. This is about twice the magnetic field amplitude produced by the Nb-Ti LHC magnets, and about 5 T higher than the one produced by the Nb_3Sn magnets being developed for the High Luminosity LHC (HL-LHC) [3]-[4]. To explore the design and manufacture of these magnets, several development programs have been initiated and were introduced in their scientific and historical context in a previous paper [5].

These programs are schematically organized within three initiatives. First, the *WP5 EuroCirCol Program* [6], exploring different magnet design options on the same basis, charged of the redaction of the FCC Conceptual Design Report. Second, a supporting *16 T Magnet Technology Program* [5], which includes a conductor development program, the electromechanical characterization of magnet components as well as the manufacture of R&D magnets. Third, the *U.S. Magnet Development Program (US MDP)* [19], initially focused to the design and manufacture of a 15 T cosθ model and to the exploration of canted-cosθ configurations.

During the last year these programs have considerably progressed in every domain. Numerous initiatives have been promoted for the development of high performance Nb_3Sn conductors worldwide. The different design options considered for 16 T magnets for the FCC are now converging into compact magnets to allow a possible integration in a HE-LHC. Moreover, the design of a new generation of R&D magnets is completed and manufacturing of the first units is in progress. Initiatives for developing FCC short model magnets of different designs are being finalized, manufacturing of the 15 T cosθ model as part of the US MDP is well advanced.

II. WP5 of EuroCirCol

The WP5 of EuroCirCol is gathering CEA, CERN, CIEMAT, INFN, KEK, the University of Geneva, the University of Tampere and the University of Twente to explore different design options for 16 T dipole magnets to give a baseline for future development. The results will be the core of the FCC Conceptual Design Report (FCC-CDR). This work is enriched by the other programs treated in this paper as well as by other synergic initiatives worldwide. A specific feature of this program is that different design options are considered with the same specification. A considerable effort has indeed been devoted to finalize optimum common design parameters and assumptions, as well as setting up and validating the design and analysis tools, in particular the ones for quench protection.

Since the beginning of the activity in July 2015, the program went through several major evolutions. In 2016 a redefinition of the conductor and load line margin parameters allowed the design of electromagnetically efficient coil cross sections, new features implemented in the common coil design allowed to partially fill the gap of amount of conductor needed with respect to the cosθ and the block-coil configurations, and finally a new concept of canted- cosθ using large cables was introduced. This year, thanks to a released constraint on the quadrupole field component resulting from the cross-talk between the two magnet apertures, the inter-beam distance could be reduced for the cosθ and the block-coil from 250 mm down to 204 mm.

Manuscript receipt and acceptance dates will be inserted here. This work was supported in part by the European Union's Horizon 2020 research and innovation programme under grant No 654305, EuroCirCol.
D.Tommasini is with CERN, 1211 Geneva, Switzerland (e-mail : davide.tommasini@cern.ch).

1.CERN, 1211 Geneva, Switzerland; 2.INFN, 20133 Milano, Italy; 3.Twente University, 7500 Twente, Netherlands; 4.CEA, 91400 Saclay, France; 5.INFN, 16146 Genova, Italy; 6.CIEMAT, 28040 Madrid, Spain; 7.KEK, 305-0801 Tsukuba, Japan; 8.Tampere University, 33100 Tampere, Finland; 9.University of Geneva, 1211 Geneva, Switzerland; 10.FNAL, Batavia IL 60510, USA; 11.LBNL, Berkeley, CA 94720, USA.

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

Furthermore, following the 2017 FCC Week [7], a reduction of the magnet dimension has been made possible by allowing a stray magnetic field of up to 0.2 T at the cryostat surface.

A. Magnet Design

Three design layouts are being explored: the cosθ, centralized by INFN, the block-coil, centralized by CEA, and the common-coil, centralized by CIEMAT. Furthermore, the study for a canted-cosθ layout is being carried out in collaboration with PSI. All designs are elaborated with the same assumptions on the conductor properties (critical current J_c of 1500 A/mm^2 at 4.2 K and 16 T, copper with RRR=100, maximum strand diameter of 1.2 mm, minimum Cu/nonCu of 0.8:1), the operational margin on the load-line for a nominal bore field of 16 T (14%, which corresponds to 18.6 T short sample bore field), the quench protection parameters (time margin of 40 ms, maximum hot spot temperature of 350 K, maximum voltage to ground of 2.5 kV including the circuit), the mechanical properties of the coils and in general the structural parameters of the materials used in the magnet.

The cross section of the cosθ design, compared to the one initially elaborated in 2015, is shown in Fig.1.

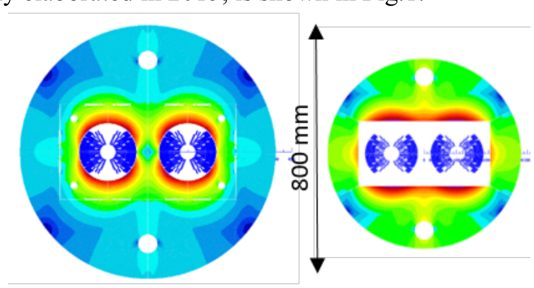

Fig. 1. Cosθ: electromagnetic cross section (left 2015, right 2017)

Each half magnet aperture features two double-layer coils made of two different cables: the two layers composing the inner coil use a keystoned cable with 22 strands of 1.1 mm diameter and Cu/nonCu ratio of 0.9, and the two layers composing the outer coil use a keystoned cable with 37 strands of 0.7 mm diameter and Cu/nonCu ratio of 2.2. The inner coil is made of 32 turns, the outer coil of 68 turns, the supply current is 11230 A and the magnet inductance (twin aperture) per unit of length is of 40 mH/m. A description of the design is given elsewhere at this conference [8].

Concerning the block-coil design, the cross section, compared to the one of 2015, is shown in Fig.2.

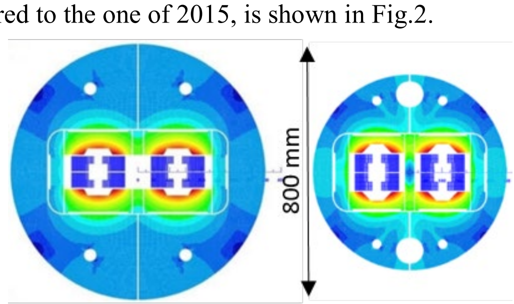

Fig. 2. Block-coil: electromagnetic cross section (left 2015, right 2017)

Each half magnet aperture features four decks composed of two double-layers coils, an upper coil and a lower coil. Each coil is internally graded using two different cables: the inner cables are composed of 20 strands of 1.15 mm diameter and Cu/nonCu ratio of 0.8, and the outer cables use 34 strands of 0.7 mm diameter and Cu/nonCu ratio of 2.0. The lower coil is made of 48 turns, the upper of 60 turns, the supply current is 10480 A and the magnet inductance (twin aperture) per unit of length is of 44 mH/m. A description of the design is given elsewhere at this conference [9].

For the common-coil, the cross section is also in this case compared to the one initially elaborated in 2015 (Fig.3).

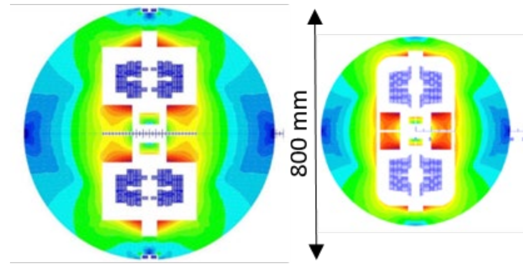

Fig. 3. Common-coil: electromagnetic cross section (left 2015, right 2017)

In this configuration, the coils are shared between both apertures. Each magnet features four 2-layers main coils made of 3 different cables: the highest field layer is made with a cable of 30 strands of 1.2 mm diameter and Cu/nonCu ratio of 1.2, the other layer of the high field coils is wound a cable of 18 strands of 1.2 mm diameter and Cu/nonCu ratio of 2.5, while the low field coils are wound with a cable of 16 strands of 1.2 mm diameter and Cu/non Cu ratio of 2.5. Besides, there are four small double-layer pole coils using the same cable than the highest field layer of the main coils. The high field main coil is made of 39 turns per layer, the low field main coil of 77 turns, and the pole coils have 4 turns per layer. The supply current is 16100 A and the magnet inductance (twin aperture) per unit of length is of 24 mH/m. The mechanical structure is based on a stainless-steel shell, which holds the Lorentz forces.

A detailed description of the design is given elsewhere at this conference [10].

Finally, the canted-cosθ cross (CCT) is shown in Fig.4.

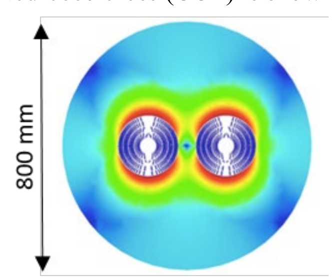

Fig. 4. Canted-cosθ: electromagnetic cross section.

The magnet features four graded CCT layers. The Cu/nonCu ratio varies between 0.8 in the innermost layer to 2.6 in the outermost layer, and the number of strand varies from 29 in the innermost layer to 20 in the outermost one. The supply current is 18025 A and the magnet inductance (twin aperture) per unit length is of 39 mH/m. The mechanical structure is based on a 25-mm-thick welded stainless-steel shell and the so-called scissors-lamination concept [11]. A description of the design is given elsewhere at this conference [12].

B. Quench Protection

The quench protection study in the EuroCirCol program has been integrated into the magnet design from the very beginning. Recently, detailed considerations on different quench protection systems and the benchmark of the simulation tools have been carried through. Particular effort has been targeted to develop coupling-loss induced quench (CLIQ) protection systems for all design options [13]. Also, a design for heater-based protection in addition to the combination of these two has been performed. These studies are suggesting that CLIQ is a promising option to protect the magnets with adequately low voltages and hot spot temperature.

C. Cost Model

The establishment of a cost model for the 16 T dipole magnets is contributing to the finalization of the design parameters. For example, assuming that a target cost for the conductor of 5 EUR/kA.m at the target performance of J_c=1500 A/mm^2, a magnet flux density of 16 T and at a temperature of 4.2 K can be achieved, it has been shown that the operation at 1.9 K with a load line margin of 14 % and a magnet aperture of 50 mm represents an ideal combination of cost/performance.

The cost model considers both an extrapolated approach from past projects, in particular the LHC including HILUMI, and an analytical approach. For example scaling the FCC-hh dipole magnet cost from LHC, taking the larger complexity and double number of coil layers into account, would yield a target cost for parts and of about 400 kEUR/magnet (50% above LHC) and for assembly 500 kEUR/magnet (75% above LHC).

The development of the analytical model includes the identification of cost-effective production methods and materials for the different magnet parts several studies are initiated in collaboration with industrial partners.

III. 16 T Magnets Technology Program

The 16 T Magnets Technology Program centralizes the technological support to the design and development of the 16 T dipole magnets for the FCC or the HE-LHC.

The main targets of the program are to:

1. improve the state of the art conductor performance with respect to the one specified for the HI-LUMI project [14], in particular to increase the critical current density (J_c) towards 1500 A/mm^2 at 16 T and 4.2 K;
2. study the conductor's electromechanical characteristics and performance with respect to its integration in the magnet through a "wound conductor program";
3. demonstrate the field reach, develop the basic magnet technology (grading and splicing, instrumentation), explore and optimize the performance (including training and field quality) with tailored R&D magnets;
4. design, manufacture and test short model magnets. This activity will start in 2018 through agreements between CERN and CEA, CIEMAT and INFN.

A. Strand development and procurement

The main technical target is to achieve a critical current density of $J_c \geq$ 1500 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), and the main commercial target is to achieve a cost of 5 EUR/kA•m at 16 T and 4.2 K. To pursue these objectives, several initiatives have been established during the year 2016. In particular three main collaboration agreements have been established: with KEK (Japan) for the development of Nb_3Sn wire at Jastec and Furukawa, with the Botchvar Institute (Russia) for the development of Nb_3Sn wire at TVEL, and with KAT (Korea). The first samples of conductors coming from these programs will be available during the year 2018.

In parallel, the conductor for feeding the magnet R&D programs is being procured: 53 km of conductor, manufactured by Bruker-OST (Fig. 5), is already available to wind the first ERMC (Enhanced Racetrack Model Coil) and RMM (Racetrack Model Magnet) magnets described in paragraph III c, and additional 290 km of wire (about 1.5 tons) are being procured to cover the magnet development program during the years 2018 and 2019. This program will thereafter require 1.5 tons of conductor per year during the period 2020-2023.

Finally, in addition to the work performed within the EuroCirCol by the University of Geneva, the University of Twente and CERN, collaboration agreements for the conductor characterization are being established with the University of Geneva, the University of Vienna and the ASC at NHMFL.

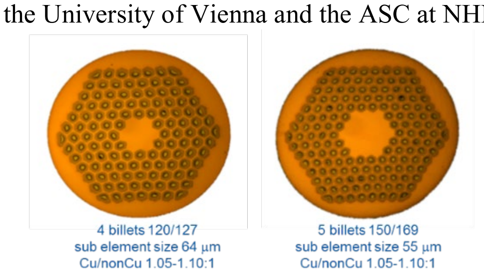

Fig. 5. Conductors for the first ERMC and RMM coils, Bruker-OST.

B. Wound conductor

This activity is developed to study the characteristics and performance of the conductor once wound, thermally treated and impregnated. The study concerns the *characterization of cable windability*, by measuring and modeling the geometrical evolution of cables during coil winding, the *mechanical characterization of cable stacks*, by measuring and modeling the stress-strain distribution in cable stacks representative of a coil cross section, the characterization of the *coil degradation during magnet assembly* as a function of the applied stress. A salient result obtained during the year 2017 has been the observation that we may have a potential to compress Nb_3Sn coils during magnet assembly (at ambient temperature) above 150 MPa of peak stress without producing a degradation of the conductor [15]. Though still preliminary and to be confirmed with more statistical elements, these results may enable new opportunities for industrial assembly of high field magnets.

C. *R&D Magnets*

Two types of magnets have been developed (Fig.6): the ERMC, a modified version of the RMC [16], and the RMM.

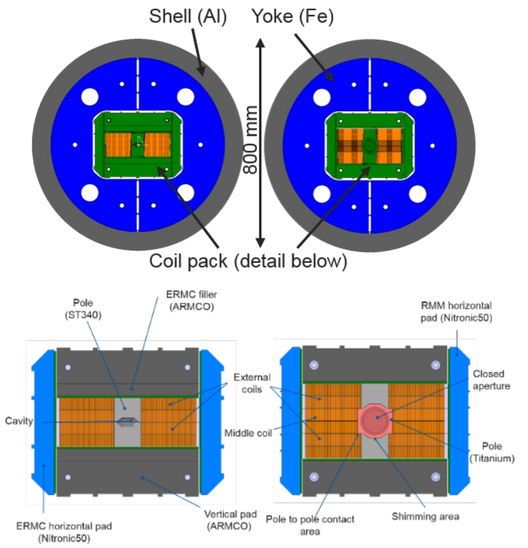

Fig. 6. R&D Magnets: the ERMC (left) and the RMM (right)

The ERMC is composed of two superposed double-pancake flat racetrack coils in a dipole configuration, having a potential to achieve a short-sample dipole field intensity in a range of 18-19 T depending on the conductor. The magnet features a relatively long "straight section" of about 700 mm, 250 mm of which occupied by the layer jump, giving the opportunity of studying the effect of different assembly and coil loading conditions on the training performance.

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

This is achieved, by inserting, at the mid-plane location between the double pancake racetrack coils of the ERMC, one additional double pancake flat racetrack coil (middle coil), creating a closed magnet bore of 50 mm diameter.

The first ERMC will be completed and tested in 2018, and the first RMM in 2019.

A more detailed description of the activities on these R&D magnets is given in [17] and elsewhere at this conference [18].

IV. The U.S. Magnet Development Program

This program is described in detail elsewhere in this conference [19]. We focus here on the 14-15 T dipole model, a key part of the US-MDP, which constitutes an important step on the roadmap towards 16 T Nb_3Sn magnets.

The magnet design concept and parameters are reported in [20], the coil cross section and a 3D view of the cold mass are pictured in Fig.7.

The coil has 4-layers graded based on two cables both 15.1 mm wide. The cable used in two innermost layers has 28 strands 1 mm in diameters and is 1.87 mm thick. The cable used in two outermost layers has 40 strands 0.7 mm in diameter and is 1.32 mm thick. The keystone angle of both cables is 0.805 degrees. The strand nominal critical current density at 15 T and 4.2 K Jc is 1500 A/mm2, and the nominal Cu/SC ratio is 1.13.

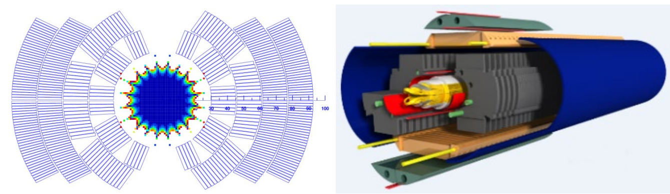

Fig. 7. Coil cross section with field quality diagram (the dark colored zone represents a field uniformity better than 2×10^{-4}), and 3D view of the cold mass.

The main elements of the cold-mass include 2 mm stainless steel spacers, iron yoke laminations, aluminum clamps, iron fillers and stainless steel shells. Quench protection heaters composed of stainless steel strips are placed between the 2nd and 3rd coil layers and on the coil outer layer.

The axial Lorentz forces in coil ends are intercepted by two thick end plates connected by eight stainless steel tie rods running through dedicated holes in the iron yoke. The magnet cold-mass is ~1 m long. The cold mass transverse size is ~610 mm, limited by the inner diameter of the Fermilab test cryostat.

The calculated maximum bore field is 15.6 T at 4.2 K and 17.3 T at 1.9 K using RRP strands with Jc(12T, 4.2K)= 2.75 kA/mm^2. However, the mechanical analysis performed at Fermilab [21] and by FEAC-U. of Patras [22] shows that the maximum design field for this magnet, when coil stress is limited by ~175 MPa and the pole turns are in contact with pole blocks, is limited by ~15 T. The results of this mechanical analysis are being verified using special mechanical model [23].

The fabrication of the 15 T dipole demonstrator is in progress. Three two-layer outer coils have been wound and cured. Two of them were reacted, impregnated with epoxy and instrumented. Winding of the two-layer inner coils is in progess. All parts of the magnet mechanical structure have been procured. The status of magnet fabrication is reported in [23]. Cold tests of the magnet are planned for spring 2018.

V. Conclusion

The development of 16 T magnets for a FCC or for a HE-LHC is organized in a well-defined framework made of a design activity, supporting technological program and a US program. In particular the work performed within the EuroCirCol collaboration will constitute the basis for the write-up of the FCC-CDR during the year 2018. By that time the technological program and the US program, accompanied by the experience gained with the development of the Nb_3Sn magnets for HI-LUMI, should have provided a number of preliminary information to support the credibility of the magnets designs described in the FCC-CDR.

Acknowledgment

The Authors would like to thank all Colleagues and Institutes providing valuable support with expert discussions and participation to reviews.

REFERENCES

[1] CERN, "The European Strategy for Particle Physics", *CERN-Council-S/106*, CERN, Brussels, 2013.

[2] Proceedings of the EuCARD-AccNet-EuroLumi Workshop, Oct. 2010, Republic of Malta, http://cds.cern.ch/record/1344820

[3] F.Savary, *et al.,* "Progress on the Development of the Nb_3Sn 11T Dipole Magnet for the High Luminosity Upgrade of the LHC*", IEEE Trans. Appl. Superconductivity,* vol. 27, no. 4, June 2017.

[4] P.Ferracin, *et al.,* "Development of MQXF: The Nb_3Sn Low-β Quadrupole for the HiLumi LHC", *IEEE Trans. Appl. Superconductivity,* vol.26, no.4, June 2016.

[5] D.Tommasini, *et al.,* "The 16 T dipole development program for FCC", *IEEE Trans. Appl. Superconductivity*, vol. 27, no. 4, June 2017.

[6] Horizon 2020 EuroCirCol Consortium Agreement, number 654305.

[7] FCC Week 2017, https://indico.cern.ch/event/556692

[8] V.Marinozzi, G.Bellomo, B.Caiffi, P.Fabbricatore, S.Farinon, A.Ricci, M.Sorbi "Conceptual design of a 16 T cosθ bending dipole for the Future Circular Collider", manuscript submitted for publication to *IEEE Trans. Appl. Superconductivity*.

[9] C.Lorin, M.Durante, H.Felice, M.Segreti, "Design of a Nb_3Sn 16 T block dipole for the Future Circular Collider", manuscript submitted for publication to *IEEE Trans. Appl. Superconductivity*.

[10] F.Toral, J.Munilla, "Magnetic and mechanical design of a 16 T common coil dipole for FCC", manuscript submitted for publication to *IEEE Trans. Appl. Superconductivity*.

[11] A. Ijspeert and J. Salminen. Superconducting coil compression by scissor laminations. Proceedings of PAC 1996, Barcelona, Spain, p. 2237–2239, June 1996.

[12] B.Auchmann, L.Brouwer, S.Caspi, J.Gao, G.Rolando, S.Sanfilippo, "Electromechanical Design of a 16-T CCT Twin-Aperture Dipole for FCC", manuscript submitted for publication to *IEEE Trans. Appl. Superconductivity*.

[13] "CLIQ", PhD thesis University of Twente, The Netherlands, 2015, doi: 10.3990/1.9789036539081

[14] L. Rossi, "Conductor choices for upgrades of CERN magnets," manuscript submitted for publication to *IEEE Trans. Appl. Superconductivity*.

[15] Patrick Ebermann, *et al*., "Characterization of irreversible degradation of Nb_3Sn Rutherford cables due to transversal compression stress at room temperature", to be presented at the 13^{th} European Conference on Applied Superconductivity, Geneva, 17-21 September 2017.

[16] E.Fornasiere, *et al.,* "Status of the Activities on the Nb_3Sn Dipole SMC and of the Design of the RMC", *IEEE Trans. Appl. Superconductivity,* vol. 23, no-2, June 2013.

[17] S. Izquierdo Bermudez, R.Ortwein, J.C.Perez, E.Rochepault, "Design of ERMC and RMM, the base of the Nb_3Sn 16T magnet development at CERN", *IEEE Trans. Appl. Superconductivity*, vol. 27, no. 4, June 2017.

[18] E.Rochepault, S.Izquierdo Bermudez, J.C.Perez, D.Schoerling, D.Tommasini, "3D Magnetic and Mechanical Design of Coil Ends for the Racetrack Model Magnet RMM", manuscript submitted for publication to *IEEE Trans. Appl. Superconductivity*.

[19] S.Prestemon, "The US Magnet Development Program for High Field Accelerator Magnet R&D", manuscript submitted for publication to *IEEE Trans. Appl. Superconductivity*.

[20] A.V. Zlobin, *et al.,* "Design concept and parameters of a 15 T Nb_3Sn dipole demonstrator for a 100 TeV hadron collider", IPAC2015.

[21] I. Novitski *et al.*, "Development of a 15 T Nb_3Sn Accelerator Dipole Demonstrator at Fermilab", *IEEE Trans. on Appl. Superconductivity,* Vol. 26, Issue 3, June 2016.

[22] C.Kokkinos *et al.*, "FEA Model and Mechanical Analysis of the Nb_3Sn 15 T Dipole Demonstrator", manuscript submitted for publication to *IEEE Trans. Appl. Superconductivity*.

[23] I.Novitski *et al.*, "Design and fabrication of a 15 T Nb_3Sn accelerator dipole demonstrator", manuscript submitted for publication to *IEEE Trans. Appl. Superconductivity*.