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Strategy for Superconducting Magnet Development for a Future Hadron-Hadron Circular Collider at CERN

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Strategy for Superconducting Magnet Development for a Future Hadron-Hadron Circular Collider at CERN

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Following the recommendation of the European Strategy Group for Particle Physics, a study on options for a Future Circular Collider (FCC) with centre-of-mass energy of 100 TeV, a luminosity of $5-10\times10^{34}\,\mathrm{cm}^2\mathrm{s}^{-1}$ and a circumference in the range of 100 km was started. The study integrates ongoing accelerator and technology initiatives at CERN, Geneva, Switzerland and in partner institutes and universities. A key technology for the FCC are high-field superconducting accelerator magnets. The FCC arc magnets need an aperture of 50 mm, with dipole fields with a target of 16 T and quadrupole gradients with a target in excess of 400 T/m. Based on these preliminary parameters, in this paper we discuss the challenges for the main magnetic elements of such a collider, and outline a strategy for the development of the required technology.

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1. Introduction

The Future Circular Collider (FCC) study responds to a request made in the Update of the European Strategy for Particle Physics where it was given a high-priority among several other accelerator options. In 2013, the FCC study was adopted by the CERN Council [1]. The FCC conceptual design phase is foreseen to span until 2018 and to be completed by publishing a conceptual design report. The target of the FCC is to push the energy frontier much beyond other proposed accelerators, so to increase the discovery potential in an affordable and energy efficient manner. All FCC options (hh, ee and ep collisions) are currently under study [2] and depending on the available time span they can be potentially and successively housed in the same tunnel, as was done at CERN already for LEP and the LHC [3]. The most challenging objective of the FCC study remains however a large circular collider (100 km) with centre-of-mass energy of 100 TeV (c.o.m).

Based on present knowledge, it can be expected that an hh-collider would provide the highest potential for discovery. However, the 100 TeV FCC option poses some major challenges, and especially for magnet technology. In order to master these challenges and achieve the performance targets outlined in this paper, accelerator magnet technology needs to advance significantly. The hh-collider requires around 5000 high-field dipoles and 800 high-gradient quadrupoles. Given this tantalizing scale, the baseline of our study relies on low-temperature superconducting (LTS) magnets up to a maximum operating field of 16 T, with in particular Nb_3Sn, as the key enabling technology. High-temperature superconductors (HTS) are an option to exceed this field barrier, and are considered as candidates for very high field accelerator magnets in programs such as the EuCARD-2 collaboration [4]. On account of the relative early stage of this technology and the difficulties to see present HTS production extrapolated to very large scale, we will not discuss this option further. The first layout of the FCC-hh has been done considering LTS only.

In Table 1, we have collected the most relevant parameters of the required high-field LTS magnets for the FCC-hh arc and insertion regions, based on beam optics considerations [5, 6, 7]. Given the present status of the study, the specifications should be intended as preliminary, and bound to adapt. The magnet types for which we could specify the required performance are: (1) the main arc dipole (MB), (2) the main arc quadrupole (MQ), (3) the separation dipole (MBX), (4) the recombination dipole (MBRB), (5) the triplet quadrupole (MQX), and (6) a generic large aperture matching section/injection/dump quadrupole (MQY) for which better optics definition is required [6].

Table 1: First considerations on magnet main parameters.

		Aperture mm	Field T	Gradient T/m	Peak field T	Length m	Units –
Main arc dipole	MB	50	16	–	16.5	14.3	4578
Main arc quadrupole	MQ	50	–	420	12.0	5.4	762
Separation dipole	MBX	60	12	–	12.5	12	4 per IP
Recombination dipole	MBRB	60	10	–	10.5	15	4 per IP
Triplet quadrupole	MQX	100	–	225	13.0	10	16 per IP
MS quadrupole	MQY	70	–	300	12	TBD	TBD

The aperture of the arc is set at 50 mm (clear bore), which is very close to the arc magnets of the LHC (56 mm). This is larger than the initial aperture of 40 mm, selected at the beginning of the study, and is necessary to host a complex structured beam screen which is required to remove the synchrotron radiation [8, 9]. The intra-beam distance is set to a tentative value of 250 mm as a compromise between the magnetic cross-talk of high field magnets, and the overall dimension of cold mass.

For the main arc dipole MB, the bore field that corresponds to an energy of 100 TeV (c.o.m.) with a circumference of 100 km, selected for siting in the CERN area, is approximately 16 T (operating), which is perceived today as the upper operating field limit of low-temperature-superconductor (LTS) technology. The length of the arc dipoles, 14.3 m, has been set as for the LHC dipoles because of the European limit on articulated vehicles (16.5 m).

Concerning the main quadrupole MQ, the gradient and length specified are consistent with the increased beam rigidity and reflect the requirements of a cell length that is doubled with respect to the LHC. A value of the gradient of 380 T/m, can be achieved with a sufficient margin employing an enhanced high-J_c wire [10]. The target gradient of 420 T/m would either require grading, or operating the quadrupoles at reduced the margin. The benefit is a shorter quadrupole length, by 10%, and more contingency for the dipole in terms of length and/or margin.

The separation MBX and recombination MBRB dipoles, in spite of the relatively lower field levels, are quite challenging. The MBX will have to deal with the heat load and radiation dose caused by the debris from the interaction point, and its aperture, 60 mm, is rather tight, and may eventually increase once better optics layout and simulation of dose become available. The MBRB has two bores with 10 T field, in the same direction. With an intra-beam distance of 250 mm it poses definite challenges of field quality because of strong cross-talk.

Apart for the unprecedented length, the quadrupoles for the interaction regions, MQX, have specifications [11] which are close to a scaled version of the IR quadrupole magnets currently developed for HL-LHC. Disregarding the unknown of radiation heat load and dose, presently under quantification, these magnets are today those that are closest to prototypes which have been realized so far.

Finally, a medium aperture quadrupole, MQY, has been defined for the matching section, injection and dump insertions. The aperture, 70 mm, is sufficient to make use of HL-LHC technology for the insertion and dumps. However, as the optics of these sections is far from being final, at present this magnet specification is to be taken as very preliminary.

Different design proposals for each of the magnets above were presented at the 'FCC Week' yearly meeting in Washington, see [12] where details of all designs can be found.

2. MB studies

Looking at the recent US and European high-field accelerator Nb_3Sn magnet programs most relevant to the FCC dipole development, it is evident that a 16 T dipole magnet is a large step forward, for which a world-wide collaborative effort will be crucial in the future.

To date the highest field amplitudes in a dipole configuration with accelerator aperture have been reached in the US (LBNL) in the D20 [13], which produced 13.5 T at 1.9 K in a 50 mm bore, and in the HD2c [14], which produced 13.8 T at 4.3 K in a 36 mm bore.

In June 2015, in the frame of the HiLumi LHC Design Study project [15], supported by the Fermi National Accelerator Laboratory (FNAL) magnet core programme [16], a single-aperture model magnet was successfully tested at CERN reaching approximately 12 T at 1.9 K [17]. The model is representative of the double aperture Nb_3Sn 11 T dipole magnets which will have to be installed in the LHC during the Long Shutdown 2 [18].

In parallel, the European Coordination for Accelerator Research & Development program EuCARD [19] and the Hi-Lumi LHC design study (WP19) [15] aim at concluding the production of a 100 mm aperture, 13 T dipole magnet, that will be used to upgrade the 'Facility for the Reception of Superconducting Cables' (FReSCa) at CERN, known as FRESCA2. The dipole developed in this programme is a Nb_3Sn, block dipole magnet with four double pancakes designed to reach up to 15 T at 1.9 K [20].

This short review of the state-of-the-art in high field magnets makes it evident that the request for a 16 T dipole (MB) calls for a technological development program. The main focus of this program will be the MB. Within the conceptual design phase (2013-2018) the MB program is organized as follows:

- A study with the aim of producing an engineering design of a 16 T accelerator model magnet at 4.5 K and with 10% margin, embedded in the frame of the European Circular Energy-Frontier Collider Study (EuroCirCol WP5) [21]. We note that an operating temperature of 4.5 K was chosen for this initial study but is not a definitive choice of the operation temperature. Obviously, if a magnet can provide 16 T at 4.5 K, it should in principle also be capable of providing the same field at 1.9 K. In addition, based on the work on the HL-LHC magnets, it seems that the necessary margin for operation at 4.5 K may be lower than at 1.9 K. This activity will take place in the period 2015-2019 at CERN and partner institutes and will concern the 16 T dipole magnet only, assuming that the quadrupole and the other magnets will not represent a show-stopper once the technology for a 16 T dipole is proven. The objective is to arrive to a manufacturing folder by mid-2019, and proceed to manufacturing using the superconductor developed within the scope of the supporting technology program. Winding would start by the end of 2019 with the aim of cold testing the magnet in 2021.

- A technology program in support of the FCC study, conveying wire and cable development as well as design, manufacture and test of demonstrators capable of producing 16 T at 4.5 K and with 10% margin in a 50 mm gap, is being organized at CERN. The program is shown schematically in Table 2. In details, the scope of this technological program is the following:

  - Nb_3Sn wire development for use in FCC magnets, with a target increase of the superconductor performance with respect to state of the art wire to reach a J_c of 1500 A/mm^2 at 16 T and 4.5 K by June 2019 [22]. This development is necessary to achieve the required magnetic field while keeping a reasonable coil size. The wire and cable development will be accompanied by a complete characterization to derive performance characteristics and limits as a function of both manufacturing processes and assembly/operating conditions in the coils (heat treatment, insulation and impregnation, structural conditions, etc.) through a tailored 'wound conductor program'. This development will provide the wire and cable necessary to manufacture the demonstra-

Table 2: Main milestones of the companion technological activity within the FCC study.

Program	Activity	Begin	End	2015	2016	2017	2018	2019	2020	2021
EuroCirCol	Design of a model magnet	01.05.2015	30.04.2019							
FCC Technology	EuroCirCol concepts	01.05.2015	30.04.2016							
	EuroCirCol analysis	01.05.2016	30.04.2017							
	EuroCirCol design	01.05.2017	31.12.2018							
	Conductor R&D	01.05.2015	30.04.2021							
	R&D wire orders	01.05.2015	30.04.2016							
	35 km wire for demonstrators	01.05.2015	30.05.2017							
	70 km high J_c wire for 16 T model	01.06.2017	30.05.2019							
	ERMC	01.05.2015	30.05.2017							
	RMM	31.12.2015	31.12.2017							
	16 T Demonstrator	30.05.2016	31.12.2018							
	16 T Model	01.06.2019	30.05.2021							

tor (approximately 35 km, see below) and the FCC 16 T model magnet (approximately 70 km);

- As a logical sequel to the CERN SMC/RMC program [23], design, manufacture and test an ERMC (Enhanced Racetrack Model Coil), with coils made using existing wire, aiming at a mid-plane field of 16 T at 4.5 K with 10% margin, by mid 2017;
- To explore the features of the magnet cross section on the final scale, design, manufacture and test a RMM (Racetrack Model Magnet) with a 50 mm cavity, with coils made using existing wire, and aiming at a central field of 16 T in the cavity at 4.5 K with 10% margin, by end 2017;
- As a final proof-of-principle, design, manufacture and test one demonstrator, producing a magnetic field of 16 T at 4.5 K with 10% margin in a 50 mm aperture. Winding would start by end 2017 with the aim of cold-testing by end 2018.

• Other companion programs are being considered by the US and Japanese National Laboratories, and may address the development of wires as well as the design and manufacture of demonstrator magnets possibly in several configurations (cos-theta, canted cos-theta or common coil).

2.1 Design considerations

Presently there are four design choices for the coil cross sections under study: block-coil [14], cos-theta [24], common-coil [25] and canted cos-theta designs [26]. Besides the coil cross-section there are a number of strategic design choices to be taken, which have a large impact on the magnet complexity and technology. The main critical parameters setting the scene for a detailed engineering design are as follows: (1) the performance of the superconductor, (2) the impact of the margin and operating temperature, (3) the nature and extent of grading, and (4) the aperture's influence on the coil dimensions and stored energy. In the following subsections, we will discuss and give general guidelines for the selection of these critical dimensions which need to be defined in the early stage of the FCC-hh study.

At the FCC field levels the magnet forces (Figure 1, left) will be around four times larger than in the LHC dipole magnets. These large forces require a careful stress management, as the stress limit of Nb_3Sn magnet coils is nowadays considered to be up to 200 MPa [27]. Also the stored energy (Figure 1, right) will bear large challenges, especially to maintain a hot-spot temperature below 300 K. The copper-to-superconductor ratio has to be selected adequately in order to limit the hot-spot temperature in case of quench. First estimates based on an adiabatic model call for Cu:non-Cu ratios of 1/1 in the inner layers and up to 3/1 in the outer layers. Inter-layer quench heaters and coupling-loss induced quench systems (CLIQ) [28] to rapidly quench the entire coil may become a must, and are under study. A detailed protection scheme is planned to be elaborated in the frame of the EuroCirCol study.

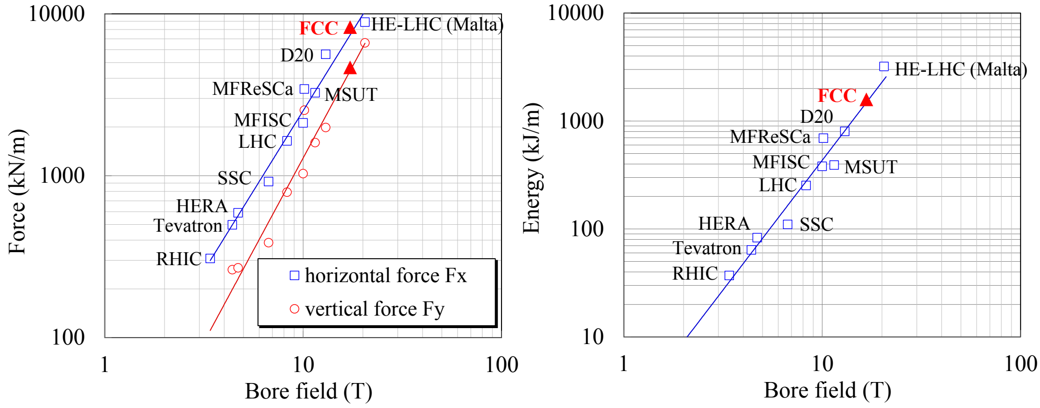

Figure 1: Comparison of forces and stored energy scaled to one aperture of FCC dipoles, reported on a general scaling plot for other accelerator dipole magnets of comparable dimension.

2.1.1 The performance of the superconductor

Nb_3Sn wire with increased current density is a necessity to meet the field goal of the FCC dipoles, keeping a reasonable coil size with the required amount of copper for protection. In addition, improved superconductor performance will help achieving part of the required conductor cost reduction. Also, better wire performance may reduce the amount of required grading layers. The target for FCC ultimate wire was set to an improvement of 1.5 in terms of current density at any given field and temperature compared to HL-LHC wire, corresponding to a target specification of 1500 A/mm^2 at 16 T and 4.5 K [22]. This target current density is in fact similar to the one already achieved with the wires used for the HD2c magnet. However, these wires had filaments of around 80 μm, which are too large to be acceptable for FCC dipole magnets [29].

The improvement of the wire translates into an increase of the current density in the superconductor in the inner layer of around 1.4 compared to HL-LHC wire (Figure 2, left). By using a high J_c wire (FCC ultimate) in a graded two layer coil, as discussed later, the gain in terms of coil cross section is large: around 1.8 times less superconductor would be required (Figure 2, right) compared to a graded coil with lower J_c wire (HL-LHC). The required superconductor area for a non-graded magnet employing HL-LHC wire compared to a graded magnet employing FCC ultimate wire is about four times larger. This discussion shows that an improved superconductor used in a graded coil has the potential to save large amounts on superconductor material, a must for a project of this size.

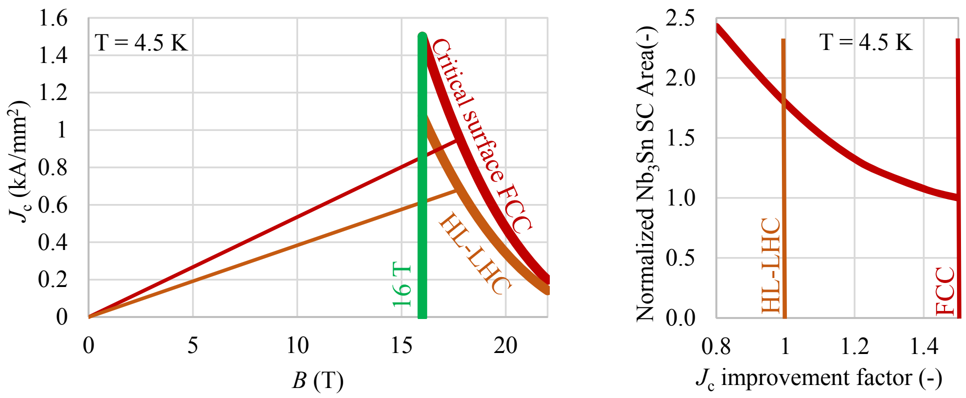

Figure 2: Load-lines for 16 T dipoles with 10% margin for HL-LHC and FCC wire (left) and normalized Nb_3Sn SC area versus J_c improvement factor for a graded 16 T dipole with 10% margin (right).

2.2 Impact of margin and operating temperature on quantity of superconductor

Operating margin is a crucial parameter. Relatively large margin is generally chosen for long strings of series-connected magnets in accelerators to decrease down time, mainly by reducing the number of quenches, during commissioning, and in the different phases of operation, including possible thermal cycles.

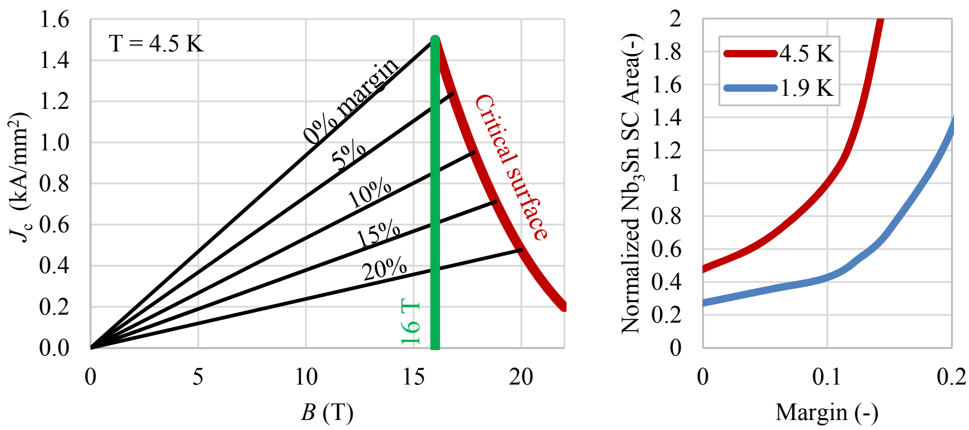

Figure 3: Load-lines for 16 T dipoles with 0-20% margin for FCC wire (left) and normalized Nb_3Sn SC area versus margin for a graded 16 T dipole wound with FCC wire (right).

The impact of the margin on the load-lines for the inner layer of a 16 T dipole magnet (with an assumed peak-field to bore ratio of 1 and margins ranging from 0 to 20%) is presented in Figure 3, left, The current density of a magnet built with no margin, compared to magnets designed for having 10% and 20% margin along the load-line, is reduced by a factor of around 1.7 and 3.8, respectively. Figure 3, right shows that these values translated to the required SC areas for a two-layer graded magnet at 4.5 K, about two and more than four times larger for 10% and 20% margin, respectively.

As a result, increasing the margin for 16 T Nb_3Sn dipole magnets increases the use of superconductor drastically and shall therefore be considered carefully. The initial conceptual design study is performed for a baseline temperature of 4.5 K and 10% margin, which translates to around 18% margin at 1.9 K for the same magnet design. The required margin and operating temperature for the FCC series magnets are one of the objectives of the supporting technology program, they will be reviewed after completing the dipole development described in this paper and the magnet design, if necessary, will be adjusted.

2.3 Importance of grading

Grading is essential because it allows for exploiting the potential of the conductors by moving the operating point of each graded layer closer to the critical surface [30, 31]. Therefore, less superconductor is required, meaning that the coil becomes more compact. A more compact coil with the same number of Ampere turns is able to produce – due to the increased geometrical efficiency – higher fields, allowing to further decrease the size of the coil. We can study the decrease of the required Ampere turns in a non-graded coil as a function of the engineering current density J_{eng} for a 60 deg sector coil by using [32]:

$$NI = \frac{B_1 \pi^2 \left(4\mu_0 R_{\mathrm{in}} \sin 60 + \frac{B_1 \pi}{J_{\mathrm{eng}}}\right)}{12 \mu_0^2 \sin^2 60} \tag{2.1}$$

A two-layer graded dipole magnet with iron yoke (30% insulation and void) generating $B_1 = 16\,\mathrm{T}$ at $T = 4.5\,\mathrm{K}$ and with 10% margin in an aperture of $2R_{\mathrm{in}} = 50\,\mathrm{mm}$ requires around 1.2 times less Ampere turns and around 2.4 times less superconductor than a non-graded sector-coil with the same performance.

These considerations indicate that grading is mandatory to use efficiently the superconductor and consequently reduce the magnet cost. The geometrical saving factor provided by grading is especially attractive because the engineering current density in the inner layer of the coil will be modest. To make effective use of grading, we propose to use high performance Nb_3Sn wire both in the inner (high-field) and in the outer (low-field) regions. Where the high J_c will allow reducing the superconductor cross section and increase the Cu:non-Cu ratio, as beneficial for protection.

Currently, we consider two-layer graded coils, which will require around 20,000 inter-coil Nb_3Sn splices between Rutherford cables (assuming the same current in all coil layers) in the 100 km accelerator. Therefore, the development of easy-to-use and reliable splicing technology will be an essential part of the FCC technology companion activity.

The use of Nb-Ti wire in the outer part of the coil where the peak field is in the order of 6-9 T (depending on the design choice) may appear appealing because Nb-Ti is relatively easy to use, readily available and low in cost. However, in the frame of the demonstrator and first model, we do not consider to use Nb-Ti in these 'low'-field regions. This choice is justified by the fact that, if the FCC target cost for the Nb_3Sn superconductor will be achieved, the cost per kA at low fields would be close for the two materials.

2.4 Aperture's influence on the amount of required superconductor

To incorporate the complex structured beam screen, required to remove synchrotron radiation and to cope with impedance and beam stability issues, a large aperture is favourable. The amount of superconductor required for the coils increases approximately linearly with the aperture, while the stored energy increases roughly quadratically with the aperture. This behaviour was confirmed with simulations for a two-layer graded coil. Taking these principles into account, an aperture of 50 mm was set as a baseline as it increases only marginally the cost of the magnets (20% larger coil, i.e., in the order of 10% larger cost for the magnet dipole system) compared to the initially assumption of an aperture of 40 mm.

3. Other magnets

The main focus of the FCC magnet program is put initially on the dipoles because they represent the largest technical and cost challenge. Nevertheless, in support to the FCC study, a preliminary conceptual design of the other magnets listed in Table 1 was discussed at the FCC Week [12]. Specifically to the MQ quadrupoles, the concept was elaborated in greater detail, and presented in [10]. The conceptual study reported there focused on the mechanical design to provide an easy-to-industrialize alternative for the FCC project to the bladder-key system currently used for the HL-LHC MQXF project [33]. The developed conceptual design is based on dipole-type collared coils with pole loading. The main features of this design concept are described in [34] and the concept is currently developed in more detail towards a full engineering design which could be tested with HL-LHC MQXF quadrupole coils and compared to the bladder-key system.

A detailed design proposal will be formulated, also taking into account the advancement of the dipole program, described above. Grading, as performed in the framework of the dipole program, may increase the gradient from the current design value of 380 T/m to the target of 420 T/m [6, 35] and reduce the amount of required wire for the quadrupoles. The technology required for the construction of such quadrupoles (improved current density wire, grading and splices) will be the natural result of the dipole program.

4. Conclusion

CERN is presently strongly engaged in the development of the superconducting magnets for the HL-LHC project. This upgrade will make use, for the first time in a collider, of high field Nb_3Sn magnets, both dipoles and quadrupoles. The efforts devoted to this activity, appropriately complemented by more tailored programs, will be the key to lead to a realistic conceptual design study of the FCC within the next four years.

Beyond the HL-LHC targets, the FCC program will cover both advanced design concepts (in particular in the frame of the EuroCirCol EU Design Study) and magnets technology aspects (the

CERN magnets technology program, and possibly companion US and Japanese programs). The main medium term targets of these programs are the increase of the superconductor performance beyond the state-of-the-art of the HL-LHC wires, attaining possibly the ultimate limits of LTS materials, and the demonstration of a 16 T magnetic field in a 50 mm dipole aperture with sufficient margin for operation in an accelerator of the scale of the FCC.

References

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

[2] The Future Circular Collider Study, *Future Circular Collider Study*, CERN, Geneva.2014.

[3] H. Schopper and S. Myers, *Eds., Elementary Particles – Accelerators and Colliders, Heidelberg: Springer*. 2013.

[4] L. Rossi, A. Badel, M. Bajko, A. Ballarino, L. Bottura, M. Dhallé, M. Durante, P. Fazilleau, J. Fleiter, W. Goldacker, E. Härö, A. Kario, G. Kirby, J. v. N. van Nugteren, G. de Rijk, T. Salmi, C. Senatore, A. Stenvall, P. Tixador, A. Usokin, G. Volpini, Y. Yang, and N. Zangenberg, *The EuCARD-2 future magnets european collaboration for accelerator-quality HTS magnets*, in *IEEE Transactions on Applied Superconductivity*, vol. 25, no. 3. 2015.

[5] A. Ball, M. Benedikt, L. Bottura, O. Dominguez, F. Gianotti, B. Goddard, P. Lebrun, M. Mangano, D. Schulte, E. Shaposhnikova, R. Tomas, and F. Zimmermann, *Future Circular Collider Study Hadron Collider Parameters, FCC-ACC-SPC-0001, CERN, Geneva*. 2014.

[6] E. Todesco, *Magnet specifications*. Washington: FCC Week, Marriott Georgetown Hotel, 2015.

[7] D. Barbara, A. Chancé, J. Payet, R. Alemany-Fernandez, B. Holzer, and D. Schulte, *First considerations on beam optics and lattice design for the Future Hadron-Hadron Collider FCC-hh, in IPAC'15, Richmond, VA*. 2015.

[8] V. Baglin, *Cryogenic beam vacuum specificities applicable to FCC-hh*. Washington: FCC Week, 2015.

[9] C. Garion, *Arc vacuum considerations, and beam screen design*, Washington: FCC Week. 2015.

[10] M. Karppinen, *Preliminary design of Nb_3Sn quadrupoles for FCC*. Geneva: FCC Magnet Meeting, 2015.

[11] R. Martin, R. Tomás, and B. Dalena, *Interaction region for a 100 TeV Proton-Proton Collider, in IPAC'15, Richmond, VA*. 2015.

[12] FCC Week, 23-29 March 2015, Marriot Georgetown Hotel, Washington, `http://cern.ch/fccw2015`.

[13] A. McInturff, R. Benjegerdes, P. Bish, S. Caspi, K. Chow, D. Dell'Orco, D. Dietderich, R. Hannaford, W. Harnden, H. Higley, A. Lietzke, L. Morrison, M. S. R. Morrison, J. Smithwick, C. Taylor, and J. van Oort, *Test results for a high field (13 T) Nb_3Sn dipole*. in *PAC'97*, Vancouver, 1997.

[14] P. Ferracin, B. Bingham, S. Caspi, D. Cheng, D. Dietderich, H. Felice, A. Hafalia, C. Hannaford, J. Joseph, A. Lietzke, J. Lizarazo, G. Sabbi, and X. Wang, *Recent test results of the high field Nb_3Sn dipole magnet HD2,* , in *IEEE Transactions on Applied Superconductivity,* vol. 20, no. 3, pp. 292–295, 2010.

[15] High-Luminosity LHC, *FP7 HiLumi LHC*, `http://hilumilhc.web.cern.ch/about/hl-lhc-project`. Geneva, CERN.

[16] A. Zlobin, N. Andreev, G. Apollinari, B. Auchmann, E. Barzi, R. Bossert, G. Chlachidze, M. Karppinen, F. Nobrega, I. Novitski, L. Rossi, D. Smekens, D. Turrioni, and R. Yamada, *Development and test of a single-aperture 11 T Nb_3Sn demonstrator dipole for LHC upgrades*, in *IEEE Transactions on Applied Superconductivity*, vol. 23, no. 3, 2013.

[17] G. Willering, *Cold powering test update DS11 T – MBHSP102*. Geneva: Personal Communication, 2015.

[18] *2nd international review of the HL-LHC 11 T dipole for DS collimation*, Geneva, CERN, 2014. `http://indico.cern.ch/event/354499/`.

[19] *Eucard programme*. Geneva, CERN, 2009. `http://eucard-old.web.cern.ch/eucard-old/index.html`.

[20] H. Bajas, B. Baudouy, V. Benda, C. Berriaud, M. Bajko, L. Bottura, S. Caspi, M. Charrondiere, S. Clément, V. Datskov, M. Devaux, M. Durante, P. Fazilleau, P. Ferracin, P. Fessia, R. Gauthier, C. Gilou, M. Guinchard, F. Kircher, P. Manil, A. Milanese, J.-F. Millot, J.-E. M. Garcia, L. Oberli, J.-C. Perez, S. Pietrowicz, J.-M. Rifflet, G. de Rijk, F. Rondeaux, E. Todesco, P. Viret, and D. Ziemaianski, *Dipole model test with one supeconducting coil; results analysed, EuCARD-Del-D7-3-1-fullfinal*. EuCARD, 2013.

[21] FCC H2020 Project, H2020-INFRADEV-1-2014-1, 2014.

[22] A. Ballarino and L. Bottura, *Targets for R&D on Nb_3Sn conductor for high energy physics*, in *IEEE Transactions on Applied Superconductivity*, vol. 25, no. 3, 2015.

[23] E. Fornasiere, H. Bajas, M. Bajko, B. Bordini, S. Canfer, G. Ellwood, P. Ferracin, P. Fessia, J. Feuvrier, M. Guinchard, C. Kokkinos, P. Manil, A. Milanese, L. Oberli, J. Perez, and G. de Rijk, *Status of the activities on the Nb_3Sn dipole SMC and of the design of the RMC*, in *IEEE Transactions on Applied Superconductivity*, vol. 23, no. 3, 2013.

[24] D. Dell'Orco, R. Scanlan, and C. Taylor, *Design of the Nb_3Sn dipole D20*, in *IEEE Transactions on Applied Superconductivity*, vol. 3, no. 1, pp. 82–86, 1993.

[25] A. Lietzke, S. Caspi, L. Chiesa, M. Coccoli, D. Dietderich, P. Ferracin, S. Gourlay, R. Hafalia, A. McInturff, G. Sabbi, and R. Scanlan, *Test results of RD3c, a Nb_3Sn common-coil racetrack dipole magnet*, in *IEEE Transactions on Applied Superconductivity*, vol. 13, no. 2, pp. 1292–1296, 2003.

[26] S. Caspi, F. Borgnolutti, L. Brouwer, D. Cheng, D. Dietderich, H. Felice, A. Godeke, R. Hafalia, M. Martchevskii, S. Prestemon, E. Rochepault, C. Swenson, and X. Wang, *Canted-cosine-theta magnet (CCT) – a concept for high field accelerator magnets*, in *IEEE Transactions on Applied Superconductivity*, vol. 24, no. 3, pp. 1–4, 2014.

[27] E. Todesco and P. Ferracin, *Limits to high field magnets for particle accelerators*, in *IEEE Transactions on Applied Superconductivity*, vol. 22, no. 3, 2012.

[28] E. Ravaioli, V. Datskov, C. Giloux, G. Kirby, and H. ten Kate and A. Verweij, *New, Coupling Loss Induced, Quench Protection System for Superconducting Accelerator Magnets*, in *IEEE Transactions on Applied Superconductivity*, vol. 24, no. 3, pp. 1–5, 2014.

[29] G. Sabbi, L. Bottura, D. Cheng, D. Dietderich, P. Ferracin, A. Godeke, S. Gourlay, M. Marchevsky, E. Todesco, and X. Wang, *Performance characteristics of Nb_3Sn block-coil dipoles for a 100 TeV hadron collider*, in *IEEE Transactions on Applied Superconductivity*, vol. 25, no. 3, pp. 1–7, 2015.

[30] L. Rossi and E. Todesco, *Conceptual design of 20 T dipoles for high-energy LHC*, in *Proceedings of the Workshop 'The High-Energy Large Hadron Collider', Villa Bighi, Malta*. 14-16, Oct. 2011.

[31] E. Todesco, L. Bottura, G. De Rijk, and L. Rossi, *Dipoles for high-energy LHC*, in *IEEE Transactions on Applied Superconductivity*, vol. 24, no. 3, 2014.

[32] L. Rossi and L. Bottura, *Superconducting magnets for particle accelerators*, in *Reviews of accelerator science and technology*, vol. 5, pp. 51–89, 2012.

[33] P. Ferracin, *MQXF design overview*, in *HL-LHC/LARP International Review of the Inner Triples Quadrupoles (MQXF) Design*, Geneva: CERN, 2014. `http://indico.cern.ch/event/355818/`.

[34] M. Karppinen, *New mechanical concept for* Nb_3Sn *quadrupole*, CERN-ACC-2014-0244, Geneva: CERN, 2014.

[35] C. Lorin, *FCC main quadrupole magnets: preliminary study at CEA*, in FCC week, Washingtion, DC, 2015.