The EuCARD-2 Future Magnets European Collaboration for Accelerator-Quality HTS Magnets

L. Rossi, *Fellow, IEEE*, A. Badel, M. Bajko, A. Ballarino, L. Bottura, M. M. J. Dhallé, M. Durante, Ph. Fazilleau, J. Fleiter, W. Goldacker, E. Härö, A. Kario, G. Kirby, C. Lorin, J. van Nugteren, G. de Rijk, T. Salmi, C. Senatore, A. Stenvall, P. Tixador, A. Usoskin, G. Volpini, Y. Yang, and N. Zangenberg

***Abstract*—EuCARD-2 is a project supported by FP7-European Commission that includes, inter alia, a work-package (WP10) called "Future Magnets." This project is part of the long term development that CERN is launching to explore magnet technology at 16 T to 20 T dipole operating field, within the scope of a study on Future Circular Colliders. The EuCARD2 collaboration is closely liaising with similar programs for high field accelerator magnets in the USA and Japan. The main focus of EuCARD2 WP10 is the development of a 10 kA-class superconducting, high current density cable suitable for accelerator magnets, The cable will be used to wind a stand-alone magnet 500 mm long and with an aperture of 40 mm. This magnet should yield 5 T, when stand-alone, and will enable to reach a 15 to 18 T dipole field by placing it in a large bore background dipole of 12–15 T. REBCO based Roebel cables is the baseline. Various magnet configurations with HTS tapes are under investigation and also use of Bi-2212 round wire based cables is considered. The paper presents the structure of the collaboration and describes the main choices made in the first year of the program, which has a breadth of five to six years of which four are covered by the FP7 frame.**

***Index Terms*—Accelerators magnets, EuCARD2, future magnets, high-temperature superconductors, superconducting magnets.**

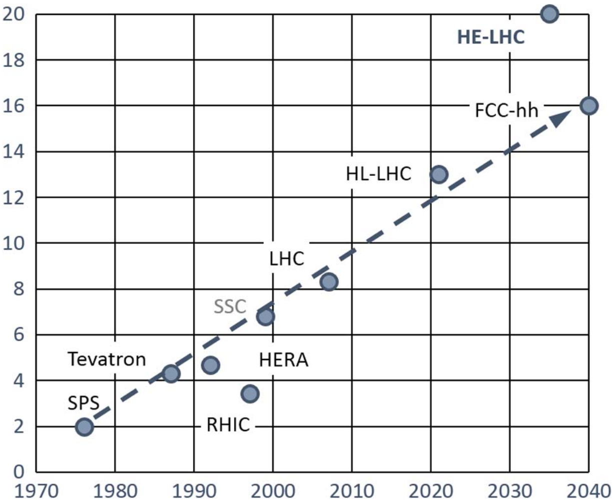

Fig. 1. Evolution of magnetic field for various particle colliders.

I. INTRODUCTION

THE DISCOVERY of the long-soughed Higgs boson [1], [2], announced at CERN on 4th of July 2012, has been the first big discovery of the LHC and also the closing of an era: the completion of the Standard Model of Particle Physics. While the LHC is being prepared to reach its design beam energy by pushing the Nb-Ti superconducting magnets [3] close to their design value of 8.3 tesla, the HEP (High Energy Physics) accelerator community is discussing the next step: the High Luminosity LHC (HL-LHC) machine [4] for which a new generation of superconducting accelerator magnets is under development [5], [6]. These magnets constitute a major breakthrough in the accelerator technology, see Fig. 1 where the progress in magnetic fields for past and future accelerator is reported. For HL-LHC peak fields in excess of 12 T for quadrupoles and 11 T for dipoles are required. For HL-LHC about 30 quadrupoles and 20 dipoles in Nb_3Sn, 4 to 7 m long, needs to be produced on the horizon of 2020. The R&D for such magnets is progressing well and the design and validation phase [5]–[9] will finish in two years, allowing starting construction in 2017.

The exploitation of HL-LHC is foreseen in the decade 2025–2035. After that time, to keep the pace and opening new lands of discoveries, a new more powerful accelerator must be built and commissioned. Time scale of more than 20 years bring us very far into the future: however it should noted that LHC, that is based on classical Nb-Ti technology, although pushed at its limits, took 25 years from first conception (established at

Manuscript received August 12, 2014; accepted October 7, 2014. Date of publication October 22, 2014; date of current version December 25, 2014. EuCARD-2 was supported in part by the partners and by the European Commission under Capacities 7th Framework Programme, Grant Agreement 312453. *(Corresponding author: L. Rossi.)*

L. Rossi is with the Accelerator and Technology Sector, CERN, 1211 Geneva, Switzerland (e-mail: lucio.rossi@cern.ch).

A. Badel and P. Tixador are with the Institut Polytechnique de Grenoble, 38031 Grenoble Cedex, France.

M. Bajko, A. Ballarino, L. Bottura, J. Fleiter, G. Kirby, J. van Nugteren, and G. de Rijk are with the CERN, 1211 Geneva, Switzerland.

M. M. J. Dhallé is with the University of Twente, 7522 Enschede, The Netherlands.

M. Durante, Ph. Fazilleau, and C. Lorin are with the CEA, Institute of Research into the Fundamental Laws of the Universe (IRFU), 91191 Gif-sur-Yvette, France.

W. Goldacker and A. Kario are with the Karlsruhe Institute of Technology (KIT), 76128 Karlsruhe, Germany.

E. Härö, T. Salmi, and A. Stenvall are with the Tampere University of Technology, 33720 Tampere, Finland.

C. Senatore is with the Departement de Physique de la Matiere Condensee (DPMC), University of Geneva, 1211 Geneva, Switzerland.

A. Usoskin is with the Bruker HTS, 63450 Hanau, Germany.

G. Volpini is with the Istituto Nazionale di Fisica Nucleare (INFN)-Laboratorio Acceleratori e Superconduttivita Applicata (LASA), 20090 Milano, Italy.

Y. Yang is with the University of South Hampton, Southampton SO17 1BJ, U.K.

N. Zangenberg is with the Danish Institute of Technology, 2630 Taastrup, Denmark.

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TASC.2014.2364215

the Lausanne workshop in 1983, [10]) to start-up on 10th of September 2008, with first high energy collisions retarded to 30th of March 2010 because of the LHC incident [11]. This is the reason why, already in 2010, CERN launched the first conceptual study for a High Energy LHC (HE-LHC), based on 20 T collider quality dipole magnets [12]–[14]. The program further evolved and got the support of the European Strategy for HEP approved by CERN Council on 30th of May 2013 in Brussels; then, in February 2014 the project grew three times as larger, to become the Future Circular Collider (FCC) [15], based on a 100 km tunnel as final goal of the next generation accelerator.

II. The EuCARD2-WP10 ≪ FUTURE MAGNETS ≫ Program and Collaborations

In 2011 a consortium among main European accelerator laboratories made a proposal to European Commission FP7-Integrating Activity, called EuCARD2. The proposal, approved in 2012 for start in 2013, includes a Work Package (WP10) on “Future Magnets,” aiming at developing HTS accelerator magnets.

This program builds upon the experience of a previous FP7 project, called EuCARD-WP7 “High Field Magnets” [16] which had the primary goal to design and build a large bore 13 T dipole in Nb_3Sn, called Fresca2 [17], with accelerator magnets technology, to be eventually used as background field for a large current (> 30 kA) high field cable test facility. EuCARD-WP7 contained also a task on the design and construction of a 6 T HTS insert for Fresca2 [18]. The focus here was on learning HTS magnet technology, study magnet coupling with a LTS background dipole, rather than verify suitability HTS for accelerator magnet technology.

A. EuCARD2-WP10 Programme

The EuCARD2-WP10 proposal document of 2011 [19], traced the roadmap for exploring the use of HTS in a HE-LHC. Dipole field in excess of 15–16 T, the Nb_3Sn limit [20], is very advantageous if the new machine will be built in the LHC tunnel (HE-LHC), see Fig. 1, given the “limited” circumference of 27 km. However, even a larger (100 km) FCC-hh (hadron-hadron) would profit of higher field, if cost is affordable. In the proposal a staged approach is described, which can be summarized as follow:

1) The main effort must be on devising a conductor suitable for accelerator magnets, which are dominated by high current density [21]. The cable current capability should be in the range of 10–20 kA, with compaction (filling) factor of 80–85% and all other accelerator (collider) characteristics, the most important being a J_E (engineering critical current density) in the single strand, tapes or wire, higher than 500 A/mm^2 at operation field, temperature and strain. Strands transposition in the cable is a must, while magnetization request comes down to a filament effective diameter of 70 μm or less and losses less than 0.01 W/m. Large currents are felt important because the HTS coils would be powered in series with 20 kA LTS cables and inductance must be kept small for protection.

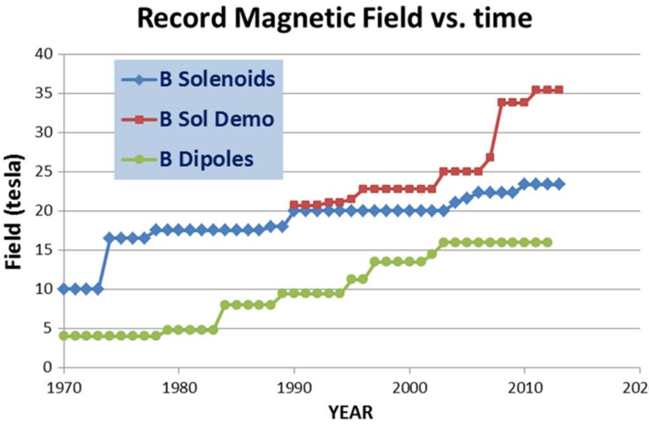

Fig. 2. Comparison between the maximum fields obtained in high field solenoids (NMR or others) and dipoles for accelerators. The gap is widening since the advent of HTS. (Some data courtesy of M. Bird, NHMFL, Florida).

2) A prototype magnet should demonstrate the suitability of the conductor to work in realistic conditions and of its ability to generate the required field shape. For this reason the main goal of this first step is building a small dipole of moderate field, in standalone mode, with near-to-accelerator quality: 40 mm free bore, 5 T central fields at 80% of I_{max} on the load line.
3) A test of the demonstrator magnet inside a high field facility, Fresca2 or other possible background field (like the recently tested Edipo [22]), would be the final stage of the path to introduction HTS into accelerators.

Therefore, EuCARD2-WP10 is a conductor program with a strong design and magnet R&D part devoted to find out how to make best use of the available conductors. Conductor is the real bridge, indeed, between materials and magnets for large devices. The 25–35 T inserts that today make record fields (for only SC magnets) in solenoids, see Fig. 2, are not really representative for accelerator quality magnet (and for other large devices). Indeed those magnets are all wound with small conductors, protected in a very special way that cannot be extrapolated over a large series of connected magnets. Traditionally solenoids feature a field only twice or less than dipole, due to intrinsic more efficient use of coil thickness, [23]. However, since the advent of HTS the gap has grown considerably, approaching a factor 3, see Fig. 2, thank to use of BSCCO and later of YBCO single tape. This show the potential of a dipole in HTS, would a suitable conductor be available.

B. The collaboration

The project WP10 “Future Magnets” was then approved and financed. It started in May 2013, for a period of four years, and ten Institutes are directly participating. The total budget is M€5.3, of which M€1.3 (out of the M€1.7 requested) provided by the EC-FP7. The remaining M€4 are provided by the Institutes as matching funds. The level of financing is about 40% of the M€3.3 direct cost only. The eleven collaborating Institutes are the following:

1) CERN-Geneva (CH), WP leader, conductor leader, magnet co-leader, test co-leader.

2) CEA- Saclay (FR), WP co-leader, conductor, magnet leader, test.
3) INPG-Grenoble (FR), conductor, magnet.
4) INFN-Milano (IT), conductor, magnet, test leader.
5) KIT-Karlsruhe (DE), conductor.
6) UniSH-University of South Hampton (UK), conductor.
7) UniGE-Univ. of Geneva (CH), conductor co-leader.
8) UT-University of Twente (NL), conductor.
9) BHTS-Bruker HTS (DE), conductor.
10) TUT-Technical Univ. of Tampere (FI), magnet, test.
11) DTI-Danish Technological Inst. (DK), magnet, test.

Since the beginning, the proposal was extended, as scientific activity and exchange, to a larger collaboration framework:

- A number of USA laboratories under the flag of "Bismuth Strand and Cable Collaboration" (BSCCO, formed by ASC-NHMFL, BNL, FNAL and LBNL), with direct funding by DOE. This is the continuation of the previous larger ARRA-DOE supported program "Very High Field Superconducting Magnet Collaboration." This collaboration is the leader in working toward the use of Bi-2212 round wire.
- Three Japanese Institutions: the HEP laboratory KEK in Tsukuba, the University of Kyoto and the Center for Life Science Technologies—High Field laboratory of RIKEN (Tokyo).

Of course the collaboration is open to a larger membership, would other partners ask to join us.

C. The WAM-HTS workshops

To support technical progress, a dedicated forum where material scientists, companies, magnet designers, and engineers can meet together, is very beneficial. One of the reasons of the slow progress of HTS is the fact that most users have been aiming at the energy/medical application sectors where collaboration is less developed for obvious reasons. But it is important to notice that the biggest advance in the past have been made by the large scientific applications, HEP and Fusion, both for Nb-Ti and for Nb_3Sn.

One of the first initiatives was to organize a series of workshops. Continuing the tradition of the workshop on Accelerator Magnets & Superconductors, from 2004 [24], a series called WAMHTS (Workshop on Accelerator Magnets in HTS) has been initiated, with an International board representing the three main regions: Asia/Pacific, Europe and North-America. The first was held in Hamburg on 21–23 May 2014, organized by CERN on behalf of EuCARD2-WP10, in the frame of the 1st EuCARD2 Annual Collaboration. WAMHTS-1 was focusing on conductor [25], and, besides people from collaborating Institutes, has seen the participation of all major companies active in HTS and interested in low temperature-high field application, as well as people from other fields. A picture of the participants is reported in Fig. 3. As shown by increasing number of works on special doping aiming at 4.2 K application [26], [27], this area, that has seen much less effort that the 77 K oriented applications (power engineering), is at present getting much more attention. This is already a positive result of the EuCARD/EuCARD2 program, as well as of other programs for high fields magnets [28]–[31] and Fusion-DEMO [32].

Fig. 3. Participants to the WAMHTS-1 in Hamburg, 21–23 May 2014.

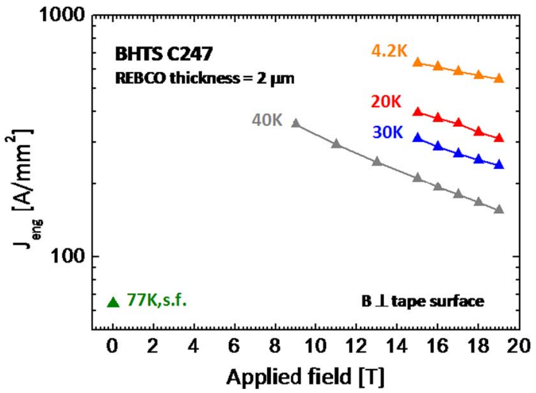

Fig. 4. First results of transport current for the EuCARD2 REBCO tape (by Bruker HTS, measurements in University of Geneva).

The next WAMHTS-2 is scheduled for 13–14 November 2014 in Kyoto, in connection with the Annual Collaboration Meeting of the HiLumi LHC project in Tsukuba. The third one is scheduled in the USA in spring in connection with a Collaboration Meeting of the FCC study. We hope that this continuity will give guidance and common targets to Industry and laboratories to make progress.

III. THE EuCARD2-WP10 ≪FUTURE MAGNETS≫ TARGETS, PLAN AND PRELIMINARY RESULTS

Since the very beginning the collaboration decided to pursue the use RareEarth$Ba_2Cu_3O_y$ (REBCO) tape based cables, rather than Bi-2212 for the following reasons:

- Continuity with the choice done in EuCARD.
- Strong interest of European Industry and European Research [33] to this material, while no Bi-2212 manufactories is present in EU.
- Larger synergy with the HTS community.
- Easy of start with a conductor that come in final form, with no need of highly complex, high temperature, heat treatment of the whole coil [34].

Fig. 5. Roebel cable concept (left); a first 15 tape Roebel cable manufactured by KIT for preliminary EuCARD2 investigation (right).

Bi-2212 development is by no means abandoned by the collaboration. A parallel effort is going on to improve the basic powder from Nexans, probably the best supplier on the market at present. The effort is pursued with a special collaboration between CERN and NHMFL-ASC in Tallahassee (Fl), with results open to EuCARD2 and wider community. The Bi-2212 effort, both on conductor and magnets is indeed integral part of the WAMHTS program. A similar collaboration between CERN, CEA and USA for sharing Bi-2212 magnet technology is also under discussion.

All targets and specifications are valid both for REBCO and Bi-2212 based conductors, even if clearly REBCO is the main goal of EuCARD2, at the moment.

A. Conductor (Task10.2) Targets and Results

The selected JE final target for the strand, tape or wire, is 600 A/mm^2 at 4.2 K and 20 T. Although the present performance of commercial REBCO at 4.2 K and 20 T in parallel field reaches record values of 2000 A/mm^2, in a perpendicular field highest J_E of 400 A/mm^2 is obtained, at best. For the first generation of EuCARD2 conductor we accept a reduced, yet challenging, minimum value of J_E of 450 A/mm^2 at 4.2 K and 20 T.

To facilitate material characterization in existing test facilities the performance target of 600 A/mm^2 at 4.2 K and 20 T has been translated to approximate values at lower field using expected field scaling. Indicative values of J_E are 675 A/mm^2 at 4.2 K and 15 T, and 750 A/mm^2 at 4.2 K and 12 T.

A minimum unit length (UL) of superconductor required is of the order of 50 m, the estimated length of a pole. A target UL of 100 m has been set for the development in the scope of Task 10.2. Homogeneity in J_E (and other properties) is important since it affects margin, performance and then cost: target homogeneity of 10% (r.m.s., with respect to average value) has been retained, which is about three times worst the present reach for Nb_3Sn.

In Fig. 4 the best results, recently obtained on a sample extracted from a 22 m long tape from BHTS, are reported. Uniformity was checked in continuous way by BHTS at 77 K self-field; however, a few samples in different zone were measured at 4.2 K and high field in field parallel to the tape surface: in all cases I_c did not show significant variation. This result is quite encouraging: however, extrapolating it to long homogeneous lengths is the big challenge.

A magnetization M target of 300 mT at 4.2 K has been taken over the volume of the superconductor, wire or tape, in all orientations, in a background field of 1.5 T ramped at 10 mT/s. When specifying this overall target for M we make no distinction between persistent and coupling currents, which will depend on the filament or tape geometry, the presence of barriers, striation and transposition.

TABLE I
MAIN TARGETS OF EUCARD2 DIPOLE AND CONDUCTOR

Parameter	Value	Note
J_E strand	600 A/mm^2 @20T,4.2K	Final target (any field direction)
J_E cable	400 A/mm2 @20T,4.2K	Minimum initial target. Final one should be > 500 A/mm^2
Cable size	10-12 mm width ~ 1 mm thickness	Bare cable before insulation, thickness at σ > 50 MPa
Magnetizat.	< 300 mT @ 1.5 T	dB/dt= 10 mT/s, all orientations
Coil inner diameter	40 mm	Free bore, available for insertion of vacuum pipe or other inserts
Central field	5 T @ 4.2 K	Standalone mode, with iron yoke, at 80 % of I_{max} on load line
Field Increase	3.9 @ 4.2 K	When inserted in a 13 T background field of high quality
Current	> 5 kA	Operat. current ~10 kA desirable
Field quality	< 5 10-4 geometric < 50 10-4 SC effects	FQ at 12-13 mm radius.
Magnet Length	~ 1 m	400 mm of straight section, 200 mm acceptable
Coil struct. outer size	< 99 mm	To fit inside Fresca2 Could be realised for standalone design.
Coil technology	React & Wind, impregnated	Pre-stress by cool down contraction of outer cylinder

A variety of cables were examined in the cable session of WAMHTS-1 [25] and the choice initially made in favor of Roebel type cable [35] was confirmed. Roebel is at present preferred because it has, almost, the same high J_{cable} as stacked tape cables, as the one for EuCARD [36]. However, differently form simple stacked cable, Roebel cable has fully transposed strands. This seems to us an essential feature for high quality magnets. In addition, because of the transposition, the length of each tape is, in average, the same in a bending section provided of course that the pitch be smaller compared to the curved length. Roebel topology, see Fig. 5, provides also: i) easy access to 10 kA class current cable; ii) ability of bending also in small radius ($R \cong 20$ mm); iii) copper amount can be easily controlled for stabilization and protection, by adding Cu tapes. Striation, through laser ablation as investigated by KIT [37] on meandered tapes for Roebel cabling, may help in reducing magnetization by persistent current, if the joints will not act as short circuit. This point needs to be carefully investigated. However, some major drawbacks of Roebel, have to be mentioned: i) impossibility to twist the strand (tape); ii) effective surface resisting to transverse stress is by far less than the total wide face of the cable and follows complicated rules just being investigated [38]; iii) to cut the meandered tapes out of the wide straight tape, typically 50% of material is lost: even if there are schemes for mitigating it (to be proved), this

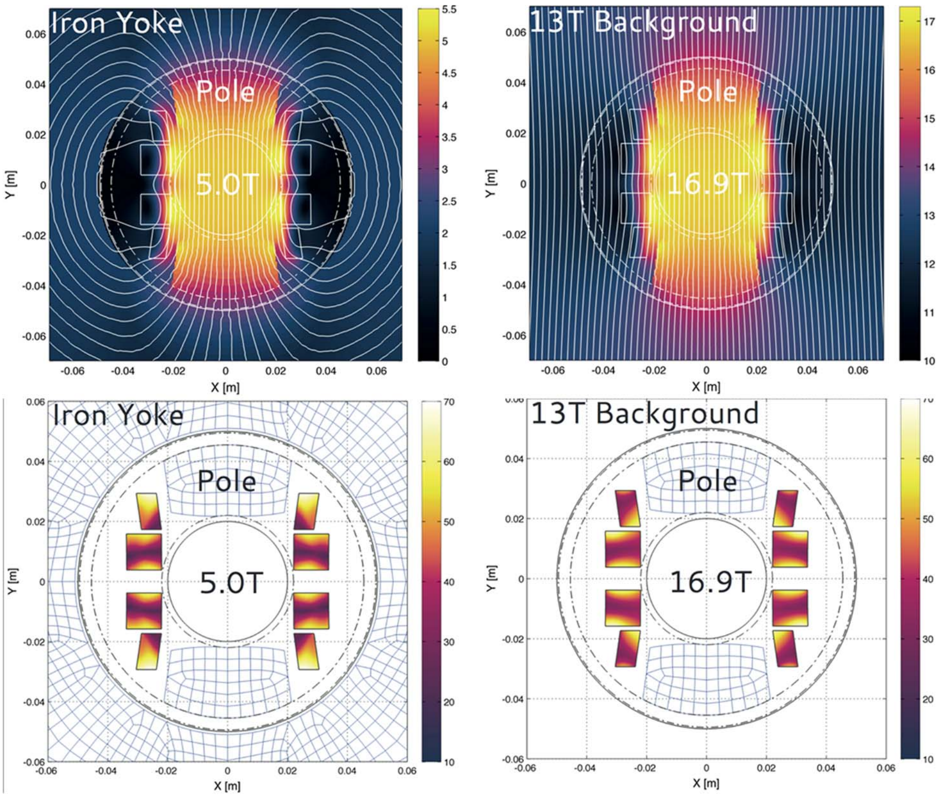

Fig. 6. Field lines (top) and 2-D coil structure with indication of near-to short regions in yellow (bottom). The pictures refer to standalone (left) and high field insert (right) configuration of the prototype dipole test.

loss weighs quite a lot for a material whose cost is very high.; iiii) the meandered shape may enhance the effect of defects, via elimination of good conductor that otherwise would act as a bypass to the defect. Striation, when applied to Roebel topology, may also worsen the impact of defects by inhibiting current sharing among parallel current paths.

The challenges are not minor, but only a complete investigation can say if they are insurmountable. The need of assessing not only normal transport and magnetization properties, but also mechanical properties and critical surface degradation in various stress configurations is critical. Therefore, a considerable part of the collaboration is dedicated to conductor, tape and cable, characterization: a thorough study of the Roebel topology and properties as well as the assessment of its potential for practical accelerator dipoles is one of the main objectives of the EuCARD2-Future Magnets programme.

B. Magnets (Task 10.3): Targets and Results

The Magnet demonstrator of EuCARD2 is to show that HTS conductor can be of profitable use in accelerator magnets. Usually the field harmonics in collider magnets are controlled to better than 1 unit (10^{-4} of the main field) at about 2/3 of the coil radius, 20 mm in our case. This means that the accuracy must be very high at 7 mm from the conductor! For our prototype we aim at a geometric dominated harmonic content of a few units, while accepting a persistent current sextupole component of some tens of units (typically is a few units for Nb-Ti and 20–30 units for Nb_3Sn).

As previously mentioned the goal of the dipole prototype is to reach 5 T with a 10 kA class cable and field quality, possibly with an iron yoke to reduce the amount of conductor, as typically done in accelerator magnets. The use of the dipole prototype as insert to boost the field of a high field facility is important but is beyond the minimum scope of EuCARD2. For the moment we plan to use the same coil design both for 5 T standalone test and for very high field insert, however designing two different coils is also possible: a final decision will be taken by the collaboration in one year. In Table I the magnet demonstrator target values for EuCARD2 are reported.

After a first preliminary exploration the various design option with REBCO, considering the strong anisotropy [39], the basic choice has been oriented toward a design called “aligned block” lay-out [40], [41]. This is a variant of the classical rectangular coil block design, however with tape/cable that is slightly inclined, to keep the field as much as parallel to wide face as possible. This can be done because the main field of a 20 T magnet is the 15 T generated by the larger LTS coils, so the insert self-field radial component is small. Our design is optimized for the high field configuration; however, at 5 T the beneficial effect of the iron yoke and pole is sensible, making our design near-to optimal also for the stand-alone 5 T configuration, see cross sections in Fig. 6.

The structure is conceived as self-supporting coil to make the insertion in various facilities easier. It mainly relies on the shrinking after cool down by the outer cylinder that contract more than the Ti-alloy winding mandrel-coil package. The maximum stresses are quite moderate at 5 T and still reasonable

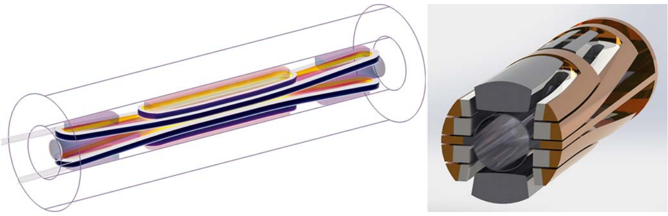

Fig. 7. 700 mm long coils of the prototype magnets showing the long end for the bending in the non-easy way of the Roebel cable (left) and artistic view of the coil structure (right), see [40], [41].

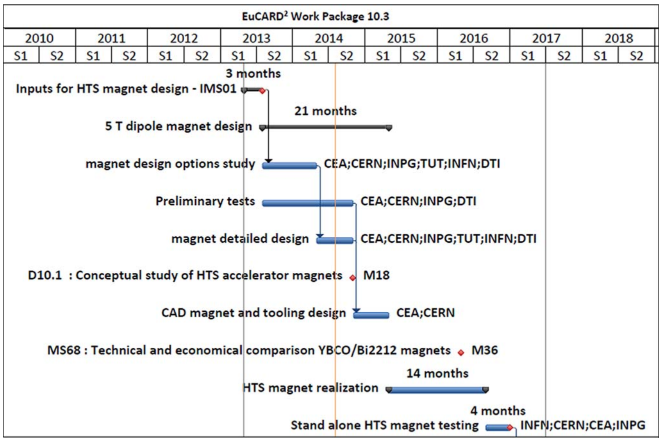

Fig. 8. Plan of the EuCARD2 magnet baseline programme.

when used as high field insert at 16.9 T (∼110 MPa): however a complete stress analysis is still to be completed. Winding tests have started as well as insulation, impregnation and compressive test on conductor stacks. Cable hard way bend tests have helped with a practical design of magnet ends. The first prototype, called Feather-2, has a 100 mm straight section with 2 × 300 mm coil ends. Of course longer magnets will have the same coil ends, see Fig. 7.

Alternative designs are not all discarded at this stage. Studies are on-going for $\cos\vartheta$ lay-out [42], or normal coil block lay-out [41], with a special care for understanding current sharing and actual critical surface of coils which are dominated by highly anisotropic tapes [39]. Additionally, we are following closely the evolution of Canted Cosine Theta (CCT) design with Bi-2212 [43], [44] and we may think to optimize it for use of Roebel, or engaging in Bi-2212 either with CCT or standard $\mathrm{Cos}\vartheta$. Stacked cable with cable twist at each turn end have been also considered [45], although at this stage with little priority. Bi-2212 is investigated at the conductor level, by contributing to the powder improvement [46]. Among other issues, protection is going to be very challenging because of slow voltage raise, as in any HTS coil, and is under careful investigation [47], [48]. The recent CERN innovation for enhanced protection, CLIQ [49] may be very useful in this respect.

C. Implementation Plan

In Fig. 8 the basic minimum implementation plan of Eucard2-WP10 "Future Magnets" program is reported. The minimum main deliverable for the program is to reach 5 T by beginning of 2017. What is in the shadow is that we aim at the end of the program also at a 10 kA cable based on tapes of $J_E = 600$ A/mm^2 @ 4.2 K, 20 T (B normal to the wide face), even if the magnet can be manufactured with 20–30% less J_E. We are qualifying, with respect to our conductor goals, also other tape suppliers worldwide [50]. The test as insert coil in the high field might be shifted to 2018 (being not an official deliverable of FP7-EuCARD2). The resources officially allocated are clearly not sufficient to complete what we call the extended programme, i.e., experimentally investigating the most promising options in alternative to the REBCO Roebel Aligned Block coil that is our workhorse. However, given the recent growing interest by several institutes, we expect that funding will be increased to allow the completion of the extended program.

IV. CONCLUSION

The EuCARD2-WP10 "Future Magnets" is a collaborative effort in the FP7 of the European Commission, led by CERN and CEA and gathering other nine Institutes, aiming at exploring HTS accelerator magnets in view of the post-LHC colliders and of other future new, or upgraded, accelerators. The effort is federating a wider collaboration in Japan and USA, organizing also a series of topical workshops (WAMHTS series). The baseline is a particular design, Aligned Coil block, which makes the best use of highly anisotropic REBCO tapes, used in a 10 kA class Roebel cable. However, various alternatives options are under investigation, too. We aim at having a real accelerator quality HTS magnet by 2017 and a high field test in 2018.

REFERENCES

[1] ATLAS Collaboration, "Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC," *Phys. Lett. B*, vol. 716, no. 1, pp. 1–29, Sep. 17, 2012.
[2] CMS collaboration, "Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC," *Phys Lett. B*, vol. 716, no. 1, pp. 30–61, Sep. 17, 2012.
[3] F. Bordry *et al.*, "The First Long Shutdown (LS1) for the LHC," in *Proc. IPAC Int. Conf. Accelerators*, 2013, pp. 44–48.
[4] L. Rossi, "LHC upgrade plans: Options and strategy," in *Proc. IPAC Int. Conf. Accelerators*, San Sebastian, Spain, 2011, pp. 908–912.
[5] L. Bottura, G. de Rijk, L. Rossi, and E. Todesco, "Advanced Accelerator Magnets for Upgrading the LHC," *IEEE Trans. App. Supercond.*, vol. 22, no. 3, Apr. 2012, Art. ID. 4002008.
[6] E. Todesco, L. Bottura, G. de Rijk, and L. Rossi, "Dipoles for high-energy LHC," *IEEE Trans. Appl. Supercond.*, vol. 24, no. 3, Jun. 2014, Art. ID. 4004306.
[7] G. Sabbi, "Progress in high field accelerator magnet development by the US LARP," High-Energy Large Hadron Collider, pp. 30–36, CERN-2011-003 (8 Apr. 2011).
[8] M. Juchno *et al.*, "Support structure design of the Nb3Sn quadrupole for the high luminosity LHC," *IEEE Trans. Appl. Supercond.*, to be published.
[9] F. Savary *et al.*, "Status of the 11 T Nb3Sn dipole project for the LHC," *IEEE Trans. Appl. Supercond.*, to be published.
[10] "ECFA-CERN workshop on large hadron collider in the LEP tunnel," Geneva, Switzerland, CERN-84-10-V-1.
[11] L. Rossi, "Superconductivity: Its role, its success and its setbacks in the Large Hadron Collider of CERN," *Supercond. Sci. Technol.*, vol. 23, 2010, Art. ID. 034001.
[12] R. Assmann *et al.*, "First thoughts on a higher-energy LHC," Geneva, Switzerland, CERN-ATS-2010-177, Aug. 2010.
[13] L. Rossi and E. Todesco, "Conceptual design of 20 T dipoles for high energy LHC," High-Energy Large Hadron Collider, pp. 13–19, Apr. 8, 2011, CERN-2011-003.

[14] A. Ballarino, "Prospects for the Use of HTS in high field magnets for future accelerator facilities," in *Proc. IPAC*, 2014, pp. 974–979.

[15] M. Benedikt, "Future circular collider study," *IEEE Trans. Appl. Supercond.*, to be published.

[16] G. de Rijk, "The EuCARD high field magnet project," *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, 2012, Art. ID. 4301204.

[17] P. Ferracin *et al.*, "Development of the EuCARD Nb3Sn dipole magnet FRESCA2," *IEEE Trans. Appl. Supercond.*, vol. 23, no. 3, Jun. 2013, Art. ID. 4002005.

[18] M. Devaux *et al.*, "HTS insert magnet design study," *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, 2012, Art. ID. 42013605.

[19] L. Rossi, "Eucard2: WP on magnets for HE-LHC: A first description," CERN, Geneva, Switzerland, CERN Rep., EDMS n, 1152224, Jul. 27, 2011.

[20] E. Todesco and P. Ferracin, "Limits to high field magnets for particle accelerators," *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, 2012, Art. ID. 4003106.

[21] L. Rossi and L. Bottura, "Superconducting magnets for particle accelerators," *Rev. Accelerator Sci. Technol.*, vol. 5, pp. 51–89, 2012.

[22] M. Portone *et al.*, "The EDIPO project: Status and outlook," *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, Jun. 2012, Art. ID. 4202905.

[23] L. Bottura and L. Rossi, "Magnets for Particle Accelerators and Colliders," in *Handbook on Devices and Applications*. New York, NY, USA: Wiley.

[24] [Online]. Available: http://amt.web.cern.ch/amt/events/workshops/WAMS2004/wams2004_index.htm

[25] [Online]. Available: http://indico.cern.ch/event/308828/

[26] V. Braccini *et al.*, "Properties of recent IBAD-MOCVD coated conductors relevant to their high field, low temperature magnet use," *Supercond. Sci. Technol.*, vol. 24, 2011, Art. ID. 035001.

[27] A. Xu *et al.*, "Strongly enhanced vortex pinning from 4 to 77 K in magnetic fields up to 31 T in 15 mol.% Zr-added (Gd, Y)-Ba-Cu-O superconducting tapes," *APL MATERIALS*, vol. 2, 2014, Art. ID. 046111.

[28] H. W. Weijers *et al.*, "Progress in the development of a superconducting 32 T magnet with REBCO high field coils," *IEEE Trans. Appl. Supercond.*, vol. 24, no. 3, Jun. 2014, Art. ID. 4301805.

[29] R. Gupta *et al.*, "Hybrid high field cosine theta accelerator magnets with second generation HTS," *IEEE Trans. Appl. Supercond.*, to be published.

[30] R. Gupta *et al.*, "HTS quadrupole for FRIB—Design, construction and test results," *IEEE Trans. Appl. Supercond.*, to be published.

[31] N. Amemiya *et al.*, "Progress of research and development of fundamental technologies for accelerator magnets using coated conductors," *IEEE Trans. Appl. Supercond.*, vol. 23, no. 3, Jun. 2013, Art. ID. 4601905.

[32] P. V. Gade *et al.*, "Conceptual design of a toroidal field coil for a fusion power plant using high temperature superconductors," *IEEE Trans. Appl. Supercond.*, vol. 24, no. 3, Jun. 2014, Art. ID. 4202705.

[33] X. Obradors and T. Puig, "Coated conductors for power applications: Materials challenges," *Supercond. Sci. Technol.*, vol. 27, 2014, Art. ID. 044003.

[34] D. Larbalestier *et al.*, "Isotropic round-wire multifilament cuprate superconductor for generation of magnetic fields above 30 T," *Nat. Mater.*, vol. 13, p. 375, 2014.

[35] W. Goldacker *et al.*, "High current DyBCO-ROEBEL assembled coated conductor (RACC)," *J Phys. Conf. Ser.*, vol. 43, pp. 901–904, 2006.

[36] Y. Miyoshi *et al.*, "Performance tests of prototype high field HTS coils in Grenoble," *IEEE Trans. Appl. Supercond.*, to be published.

[37] S. Terzieva *et al.*, "Investigation of the effect of striated strands on the AC losses of 2G Roebel cables," *Supercond. Sci. Technol.*, vol. 24, 2011, Art. ID. 045001.

[38] J. Fleiter, A. Ballarino, W. Goldacker, and A. Kario, "Characterization of Roebel cables for potential use in high-field magnets," *IEEE Trans. Appl. Supercond.*, to be published.

[39] J. van Nugteren, "Case study for a five Tesla HTS research-magnet," CERN, Geneva, Switzerland, Tech. Rep. EDMS-1389718, Jun. 2014.

[40] J. van Nugteren *et al.*, "Study of a five Tesla HTS research magnet using an an isotropic ReBCO cable," *IEEE Trans. Appl. Supercond.*, to be published.

[41] G. A. Kirby, "Accelerator quality HTS dipole magnet demonstrator designs for the EuCARD-2, 5 Tesla 40 mm clear aperture magnet," *IEEE Trans. Appl. Supercond.*, to be published.

[42] C. Lorin *et al.*, "Cos-theta design of dipole inserts made of YBCO-Roebel or BSCCO-Rutherford cables," *IEEE Trans. Appl. Supercond.*, to be published.

[43] S. Caspi *et al.*, "Design of a 18 T canted-cosine-theta superconducting dipole magnet," *IEEE Trans. Appl. Supercond.*, to be published.

[44] A. Godeke *et al.*, "Bi-2212 canted-cosine-theta coils for high field accelerator magnets," *IEEE Trans. Appl. Supercond.*, to be published.

[45] A. Badel, talk presented at WAMHTS-1, see [25], unpublished.

[46] C. Scheuerlein *et al.*, "Influence of the oxygen partial pressure on the phase evolution during the melt processing of Bi-2212 superconducting wires," *IEEE Trans. Appl. Supercond.*, to be published.

[47] E. Härö, J. Järvelä, and A. Stenvall, "Variation of quench propagation velocities in YBCO cables," *IEEE Trans. Appl. Supercond.*, to be published.

[48] T. Salmi and A. Stenvall, "Modeling quench protection heater delays in an HTS coil," *IEEE Trans. Appl. Supercond.*, to be published.

[49] E. Ravaioli *et al.*, "First experience with the new coupling loss induced quench system," *Cryogenics*, vol. 60, pp. 33–43, Mar./Apr. 2014, covered by EU Patent EP13174323.9.

[50] C. Senatore, talk presented at WAMHTS-1, see [25], unpublished.