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Report on recommended accelerator magnet follow-up R&D: Milestone M5.5

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MILESTONE REPORT

RECOMMENDED ACCELERATOR MAGNET FOLLOW-UP

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Abstract:

This milestone documents the gap analysis between findings of the study, towards a realization project: Portfolio of suggested R&D topics related to the domain of superconducting accelerator magnets and associated technologies.

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TABLE OF CONTENTS

1. 16 TESLA SUPERCONDUCTING MAGNET

1.1. MOTIVATION

At the design stage of the LHC, the dipole field level was chosen to give the highest collision energy possible with Nb-Ti technology, cooling the magnets to 1.9 K and operating them with a 14 % margin on the load line. For the future hadron collider, a similar approach is used. The goal is to fill the 100 km long tunnel with magnets that can provide the highest achievable field using the technology, which provides the best cost/performance ratio. With Nb_3Sn superconductors, hadron beams of 50 TeV can delivered in a 100 km long circular accelerator with bending magnets with a nominal field of 16 T.

This is about twice the 8.3 T generated by the Nb-Ti magnets in the LHC and about 5 T higher than the 11 T of the Nb_3Sn-based dipole magnet of the high-luminosity LHC upgrade.

The cost of such superconducting magnets is dominated by the amount of conductor. The cost increases rapidly when the operating parameters approach the conductor's critical surface. Consequently, to be able to exploit the full potential of the conductor in order to achieve the required field and quality, the smallest possible margin on the load line needs to be chosen.

1.2. OBJECTIVES

The goal is to develop a viable design for a superconducting 16 T, dual-aperture magnet. The design needs to be verified using simulations first and then with short, ca. 1.5 m long models. Eventually, full-scale models need to be built to validate the design. This programme depends on a separate R&D programme for the development of a high-performance, cost-effective Nb_3Sn superconducting wire. For the R&D phase, it is assumed the FCC-hh will work with the same 14 % margin on the load line as was adopted for the LHC. The programme aims to achieve a margin which is lower than for today's state-of-the-art Nb_3Sn HL-LHC magnets, where the it ranges between 20 and 22 %.

A main concern is to achieve reliable operation with a margin of 14 % and to reduce it further to 10 %. It is also necessary to reduce the amount of superconducting magnet training needed, so that initial test times are shorter and consequently fewer resources are needed. Eventually, operation during the nominal thermal cycle must be demonstrated.

1.3. DESCRIPTION OF WORK

The programme spans three distinct domains:

1. The development of magnets based on different designs and manufacturing technologies.
2. The design, construction and verification of magnet components and partial magnets for R&D purposes.
3. The verification and validation of model magnets.

The design studies aim to develop various feasible concepts for a high-field accelerator magnet. The designs will be verified and compared using electromechanical performance simulations including their behaviour under mechanical stress. The design process includes the identification and specification of new structural components for the ferromagnetic yoke and the coil end spacers and wedges. It also includes the development and specification of new resin impregnation systems and the development of advanced internal splicing techniques for the superconducting cables. The design process will also lead to the development of an in-depth understanding of the mechanical conductor and coil stack properties corresponding to the various manufacturing processes (insulation materials and layout, heat treatment and impregnation).

The construction of magnets for R&D purposes is based on the study of short model coil (SMC), enhanced racetrack model coil (ERMC) and racetrack model magnet (RMM) assemblies. The SMC is used as an intermediate stage to determine the effectiveness of the technologies developed for training improvements, conductor insulation and impregnation resins, as well as specific production steps, in particular the adhesion conditions between coil and poles.

ERMCs are developed in two variants with non-graded and with graded coils. They facilitate the assessment of strategies for coil manufacture and assembly, namely the interface between conductor and end spacers or conductor and pole, heat treatment and impregnation conditions (volume, stress), internal splices for the graded versions, loading conditions to minimise degradation and training and finally, the management of transitions (layer jump, ends). Eventually, ERMCs will demonstrate that the field level of 16 T can be achieved with some margin and with limited or no training.

The RMM and the ERMC share the same structure but the insertion of an additional coil between the two pancakes of the ERMC creates an aperture of 50~mm over a straight section of 470 mm in addition to a 250 mm layer jump. The structure will be designed to contain large longitudinal rods made of stainless steel or aluminium, tightened in different ways to explore various conditions of longitudinal loading, including extreme situations of nearly rigid boundaries.

These magnets will enable the training performance for a straight section of a real accelerator magnet to be determined. In addition, the measurement of the magnetic field in the aperture will be possible, even in the absence of free

access from the ends. Finally, the magnetisation effects over the powering cycle, including reproducibility from cycle to cycle as a function of the injection field will be recorded.

By building short models of all the viable options explored by the EuroCirCol H2020 project, the cosine-theta, block coils, common coils and canted cosine-theta designs can be verified under realistic conditions. Eventually, full-scale models of the most promising designs have to be constructed to validate the approach before a decision to launch a construction project for a high-energy hadron collider can be taken.

1.4. COLLABORATION WITH UNIVERSITIES AND RESEARCH CENTRES

From the beginning this R&D programme has been a collaborative endeavour which builds on the committed involvement of universities and research centres from around the world. The EuroCirCol H2020 project initiated a worldwide consortium to develop and explore designs of different high-field accelerator magnets. Research institutes with established track records in the design and development of superconducting high-field magnets need to intensify their contributions further. Model magnets are already planned to be constructed by CERN (international organisation), CEA (France), CIEMAT (Spain), INFN (Italy), PSI (Switzerland) and Fermilab (USA). The design, construction and testing activities include the cooperation of well-known institutes and universities such as EPFL (Switzerland), KEK (Japan), Technical University of Tampere (Finland), Karlsruhe Institute of Technology (Germany), University of Patras (Greece), University of Twente (The Netherlands), University of Geneva (Switzerland), National High Magnetic Field Laboratory (USA), Brookhaven National Laboratory (USA) and Berkeley Lab (USA). In particular, the high-field magnet development programme led by the Department of Energy (USA) will be a crucial factor on the way to determine a viable design for a 16 T magnet. In the near future, the consortium needs to be enlarged with additional academic partners, in particular universities and institutes in Russia with a track record in the development of high-field superconducting magnets. The consortium also needs the involvement of academic partners in Asia and more regional partners in North America, including Canada.

1.5. COLLABORATION WITH INDUSTRIAL PARTNERS

The design and development of the 16 T magnet relies strongly on the capability to manufacture, install and operate a large number of devices. Therefore, industrial partners will be included at all stages of the R&D programme, from the development of fundamental technologies from assembly and process-related activities to quality management, installation, maintenance and repair concepts. Co-development with industrial partners during the R&D phase prioritises the following key topics: automated winding systems with integrated quality control, quality improvements and resource optimisation of impregnation and heat treatment, the optimisation of assembly, the optimisation of internal and external interfaces to improve assembly, testing, installation, maintenance and repair. These activities will include the definition of collaborative EC co-funded projects to increase the impact of transferring technological developments from research to industry.

2. LOW TEMPERATURE SUPERCONDUCTOR

2.1. MOTIVATION

The feasibility of a 16 T superconducting accelerator magnet with two apertures of 50 mm each depends on the availability of an affordable conductor that can deliver a current density (Jc) of at least 1500 A/mm^2 at 4.2 K and 16 Tesla. If a high-energy hadron collider were to be built as an immediate next step after the LHC/HL-LHC programme, Nb_3Sn is seen today as the only superconducting material that can be produced at the rate and in the quantity needed for a series production of thousands of magnets by 2030. This material is being produced for use in the magnets of the HL-LHC upgrade project, the first application of Nb_3Sn technology in a particle accelerator. Industrial production of such wire is presently contracted to one leading company in the field (Bruker) that masters two processes: the Rod Restack Process (RRP©), a variant of internal tin and powder-in-tube (PIT). A Jc performance of up to 1200 A/mm^2 at 4.2 K in a field of 16 T is achievable at the time of writing this report and is therefore considered to be the current state-of-the-art. The push to reach higher critical current density to meet the target requires extensive material science research effort and the development of new manufacturing technologies.

High critical current density is necessary, but not sufficient. Dynamic and adiabatic stability, field quality and protection considerations as well as a need for high-current in compact Rutherford cables call for small superconducting sub-elements, low resistivity of the matrix stabiliser and good mechanical properties.

The conductor research and development programme launched by the FCC study aims to develop a Nb_3Sn conductor that can meet all those needs. This programme is based on a network of academic institutes and industrial partners worldwide that are tied together by an FCC R&D agreement. This network has started to investigate routes to reach the performance goals, including the production of R&D wires by four industrial partners, complemented by advanced characterisation and the investigation of novel approaches by academic partners. The programme aims first to verify different approaches and then to validate a viable technology in a full-scale magnet. For the series production of the particle collider magnets, about 8000 t of superconducting material will be needed. Therefore, the initiative is also a first step in the direction of preparing the ground for a credible large-scale supply chain on a global scale.

Affordable wire cost is the ultimate goal of the conductor programme. Since the early research and development phase, effort has been focused on production processes that appear promising in terms of scalability and that show potential for industrial low-cost production. The target maximum cost, derived from magnet design and conductor analysis, is 5 euro/kA at 4.2 K and 16 T.

2.2. OBJECTIVES

The main objective is to achieve a performance of 1500 A/mm^2 at 4.2 K and 16 T in order to achieve a Jc of at least to 2300 A/mm^2 at 1.9 K and 16 T - the latter are the operating conditions set for the magnet. The full set of objectives are outlined in the Table 1.

Table 1: Target parameters for the conductor of 16 T magnet series production

Parameter	Value	Unit
Wire diameter	~ 1 mm	
Non-copper Jc (4.2 K, 16 T)	~ 1500 A/mm^2	
Copper to non-copper ratio	0.8 : 1	
Sub-elements effective diameter	20	µm
Magnetisation – µ o δ M (4.2 K, 1 T)	< 150	
Residual Resistivity Ratio	≥ 150	
Wire unit length	≥ 5000	M
Cost (4.2 K, 16 T)	≤ 5	Euro/kAm

Smaller sub-element diameters are important to limit losses in coils during transients (acceleration ramp), to ensure dynamic and adiabatic stability and to achieve the required field quality. State-of-the-art Nb_3Sn wires have sub-elements diameters of about 50 µm. Obtaining smaller sub-element size together with higher Jc and high RRR are requirements are conflicting requirements. This is the challenge that the conductor development programme faces.

2.3. DESCRIPTION OF WORK

The main focus of the work is the development of a high-performance Nb_3Sn wire using a variant of the internal tin process. Different wire layouts have to be developed and studied in collaboration with industry, including both common and separated (distributed) barrier designs. Industrial partners will produce R&D billets in order to prototype new methods and layouts, validate industrial scalability and produce wire that industry can also assess for applications beyond particle physics applications.

The conductor programme needs to be pursued concurrently with the magnet development programme, accompanying the development and verification of short and long model magnets. The programme progresses through three stages:

1. Development of novel wire layouts and compositions;
2. Industrial production of medium size billets;
3. Development of cost-efficient, large-scale industrial production of large billets.

Task 1) focuses on studying and developing novel wire layouts and compositions with improved critical current and high RRR properties. The Nb_3Sn wire successfully produced for the HL-LHC upgrade project does not indicate a way to achieve the target performance through further, gradual optimisation. Therefore, the development a novel process is highlighted in this activity, prioritising improved Jc and RRR over properties such as the sub-element size. ”Internal oxidation” is considered a potential route towards a substantial improvement of the conductor in-field performance. Only limited work has been performed by the community to date, but preliminary results are promising.

Both industry and research laboratories have taken up this challenge, but further fundamental research is required.

Task 2) extends from understanding the fundamental material properties in model system configurations to the production of small amounts of wire for research purposes. The development needs to also include wire performance indicators such as the effective filament diameter. Test samples will be produced in simplified configurations (e.g. material layers, mono-filaments) up to small-size billets of a few kilometres for selected routes. Independent academic partners will perform extensive analysis of electro-magnetic, mechanical and thermal properties, as well as advanced analysis such as SEM, TEM and XRD. This research is an iterative process, during which results from wire manufacturing and testing provide feedback for improved designs. Experimental work, materials analysis and testing are at the core of this activity, including optimisation of heat treatments, study of tin diffusion and wire composition, in-depth micro-structural analysis, study of phase transformations, preliminary evaluation of mechanical properties and measurement of in-field electrical and magnetic properties are typical investigations that need to be performed. Experimental work, material analysis and testing/analysis are at the core of this activity.

Task 3), the production of medium-sized billets by industrial partners aims to validate the most promising R&D layouts in billets of industrial scale, increasing the technological readiness of the most promising designs that emerge from the wire R&D activity. The goal is to produce a few tens of kilometres of wire. This up-scaling and industrialisation will be accompanied by further wire design improvements in order to meet all additional requirements: stable and controlled magnetisation, filament diameter, mechanical properties. Achieving this objective will require further progress in wire design and layout. It is therefore an iterative development loop. At this stage, in addition to wire measurements and testing, the qualification of wires in Rutherford cables will begin. Short cable samples will be tested and, according to the results, will be used for short model coils. For each wire layout, production of Rutherford cables requires specific developments with iterative studies, production runs, optimisation of cable geometries and heat treatments and electro-mechanical and magnetic measurements.

The time necessary to perform tasks 1) and 2) is expected to cover a period of about ten years. During these phases, the production of about 1.5 t of conductor per year is needed to be able to meet the requirements for testing, development of cables and short model coils and to build short magnet models. The production and measurement of model coils is essential to provide feedback to the conductor programme. Conductor and magnet R&D therefore proceed in a synchronised manner and are closely interlinked.

Task 4), covers the implementation of cost-efficient, large-scale production of large billets. The industrial production processes need to be developed and validated for wire architectures that meet all objectives, including the full target performance. This part of the programme aims to show the feasibility of the production of long conductor lengths of up to 5 km in a cost-effective manner. Ultimately, large quantities, in the order of hundreds of kilometres of wire with the target characteristics will be required to feed the optimised Rutherford cable production for the long model magnets and prototype magnets.

2.4. COLLABORATION WITH UNIVERSITIES AND RESEARCH CENTRES

From the beginning, this R&D programme has been a collaborative endeavour requiring the committed involvement of universities and research centres world-wide. The EuroCirCol and EASITrain H2020 projects catalysed the establishment of a solid set of committed academic partners to make progress in fundamental materials research.

The Technical University of Vienna (Austria) is leading the microstructural analysis of superconducting wires by electron microscopy, including analysis of tin concentration gradients, artificial pinning and correlations of superconducting properties, to support wire optimisation. Technical University Bergakademie Freiberg (Germany) has launched a project to investigate phase formation in the ternary Cu-Nb-Sn system. In its fundamental material research programme, the University of Geneva (Switzerland) is exploring ways of reducing the grain size using an internal oxidation method, thus advancing wire performance. This is complemented by a project with the Applied Superconductivity Center at Florida State University in the US, which is investigating novel alloys and internal oxidation methods, and will propose routes for industrial scale-up. Wire development and analysis in Japan is coordinated by KEK, the high energy accelerator research organization, as part of a collaboration agreement with CERN. This programme includes the participation of manufacturers (JASTEC and Furukawa) and academic partners, including the University of Tohoku. The Bochvar Institute (Russia) is experimenting with various layouts of internal tin wires which show a significant performance increase, currently reaching 1200 A/mm^2 at 16 T and 4.2 K.

2.5. COLLABORATION WITH INDUSTRIAL PARTNERS

The establishment of a representative set of industrial partners who participate in the improvement of Nb_3Sn wire performance is vital for the preparatory phase of a high-energy hadron collider project. Therefore, in 2016 the FCC collaboration launched a conductor R&D programme involving industry. To date JASTEC and Furukawa in Japan, KAT in South Korea, TVEL, including the Bochvar Institute in Russia and Bruker EAS in Germany have joined the effort. The participation of Luvata Pori in Finland is planned. Three of these partners have already produced R&D billets achieving the Jc performance specified for HL-LHC with wire layouts not previously explored for this application, establishing a good baseline for further development towards the project’s performance target.

3. HIGH TEMPERATUR SUPERCONDUCTORS

3.1. MOTIVATION

The accelerator dipole magnet under design for the FCC-hh which is based on Nb_3Sn technology would generate the highest possible field that can be reached by low-temperature superconductor (LTS) materials. High-temperature superconductor (HTS) materials are the only technology that can lead to accelerator magnets with fields beyond the 16 T limit. In addition, HTS materials come with the benefit of a high temperature margin during operation, making them compatible with scenarios that are subject to high heat load and high radiation levels. If the LHC/HL-LHC research programme is followed by an intensity-frontier lepton collider (FCC-ee) with a physics programme duration of about 15 years, a new time window appears for the development of high-field accelerator magnets based on HTS for an energy-frontier hadron collider at a subsequent stage.

Besides research, industry is also considering HTS materials such as ReBCO and BSCCO for diverse applications. The main motivation is the potential of operation at higher temperatures than those that are used today in industrial and medical devices. Although refrigeration based on liquid helium is feasible even for a large research facility such as the FCC-hh, a cryogenic plant for industrial applications imposes cost and maintenance constraints that limit the application of superconducting technology. Higher operating temperature simplifies the system and eases the diffusion into commodity markets.

A higher operating temperature is also relevant for a large-scale particle collider. The cryogenic efficiency of the refrigerator would be improved, though this effect is not directly proportional to the temperature increase. A high cryogenic temperature cooling scheme (e.g. supercritical helium flow) may be less efficient than the current scheme based on superfluid bath cooling. The interest comes from the potential to intercept synchrotron radiation, the major source of heat load in the hadron collider, at a higher temperature.

The higher field reach opens routes to energy upgrades of particle colliders with magnets reaching fields of 20 T and beyond. The peculiar properties of HTS materials lead to a situation in which the challenge of designing the magnet system will shift from field reach and current limitations to mechanical aspects, protection systems and cost-effective design. The latter are topics which are easier to manage with modern design tools and manufacturing approaches.

HTS materials are still prohibitively expensive with volumetric costs that are at least an order of magnitude higher than state-of-the-art low temperature superconductors. However, with larger quantities being manufactured, with materials beginning to mature and considering the Total Cost of Operation (TCO), break-even is expected to occur within the horizon of a future hadron collider even at price levels slightly above those of the Nb_3Sn target.

3.2. OBJECTIVES

The first objective of an R&D programme on alternative superconductors is to identify those materials which have the highest probability of meeting the target performance for the high-field accelerator magnets. At the same time, they must be produced at a cost, which leads to an overall TCO (combined CAPEX and OPEX) that is much lower than a Nb_3Sn based machine. Current potential candidates for different use-cases in the particle accelerators include rare-earth barium-copper oxide ReBCO (YBCO) and Bi-2212, and possibly iron-based superconductors (IBS) if their high-field performance can be demonstrated within a reasonable time scale. These materials all pose major technological challenges for their use in accelerators. The main challenges for ReBCO are cable assembly, protection and field quality, while for BSCCO the magnet manufacturing with a high-temperature step and mechanics are the main concerns.

Today, work is focusing on developing HTS wires that can be produced in quantities that are sufficient to build accelerator-quality magnets in the 3 to 5 T range. The aim is to approach 8 T before the end of the decade. The levels of technological readiness are heterogeneous for the different materials: while for some coated conductor tapes the investigations already aim at larger-scale quality production and achieving usable fields and adequate field qualities for particle accelerator magnets, novel conductors such as IBS are still to be considered laboratory developments for which research focuses on fundamental material properties. Once the candidates are defined, a well-focused R&D programme has to be established to drive the development of conductors to achieve the required high fields and towards production processes for wires or tapes in sufficient quantities of adequate quality.

3.3. DESCRIPTION OF WORK

This research, which today still needs to be classified as basic, for the validation of basic components (e.g. the coils) in laboratory environments will need to work in the following directions in order to demonstrate high-fields at accelerator-magnet grade field quality at acceptable total cost of ownership:

- Identify the most promising materials and the main challenges associated with them in terms of performance, production and cost. Set long-term development targets for overall performance (electrical, mechanical) and realistic cost for each variant;
- Define performance targets and develop a suitable conductor for magnets, starting either from tape or wire, depending on the material. A specific challenge is finding a suitable cable topology for material that comes in tapes (ReBCO, IBS, Bi-2223). Specifically, for Bi-2212, develop manufacturing, insulation technologies and industrial reaction processes for large coils that suit the highly brittle material;
- Develop a design for a magnet system with the required field quality from injection (low field) to collision (high field) and which manages the mechanical and protection aspects. Study several HTS material options and identify the leading technology questions for each of the variants;
- Understand how materials, cables and coils behave under high stress and strain conditions;
- Acquire an in-depth understanding of the quench behaviour in order to identify suitable approaches for quench detection and quench protection. HTS materials behave differently to LTS and today's methods do not seem appropriate for these materials. In particular, the larger temperature margin may avoid the training phase and by developing early detection of quench onset it would be possible to avoid a fully developed quench. This would shorten commissioning and significantly improve accelerator availability;
- In the long-term, develop suitable high-volume and low-cost manufacturing routes and techniques for HTS materials. Demonstrate the manufacture of tens of kilometres of conductor at acceptable quality and sufficient homogeneity.

3.4. COOPERATION WITH UNIVERSITIES AND RESEARCH INSTITUTES

The ongoing R&D on Nb_3Sn and the investigations of HTS for beamscreen coatings has already created a core of collaborating academic partners, which can also serve as the starting point for a well-focused, long-term high temperature superconductor R&D programme. It federates universities with knowledge in fundamental material sciences and research centres worldwide with the possibility to build up laboratories and infrastructures to perform such a long-term research programme. However, a coordination body is yet to be defined and set-up. This body will ensure that the research and development is carried out in a topically complementary fashion with a clear convergence towards the objective and with clearly defined knowledge ownership and access policies.

The set of loosely-associated academic partners today includes Bochvar Institute (Russia), CERN, CNR-SPIN (Italy), EPFL (Switzerland), ETH Zurich (Switzerland), Florida State University (USA), FNAL (USA), KEK (Japan), KIT (Germany), LBNL (USA), NHMFL (USA), PSI (Switzerland), TU Bergakademie Freiberg (Germany), TU Wien (Austria), CEA (France), cooperative efforts of various INFN institutes (Italy), University of Geneva (Switzerland) and University of Genoa (Italy).

3.5. COOPERATION WITH INDUSTRIAL PARTNERS

The creation of a long-term, forward looking technology advancement programme also permits SMEs to play a leading role at the forefront of a technology and provides opportunities to grow with the technology in a risk-controlled environment. In addition to established players such as Bruker, Fujikura, Nexans, Sunam, SuperPower, SuperOx and Theva companies like nGimat and MetaMateria and other companies worldwide have started to participate in the investigations. As with the academic partners, a defined governing structure and the definition of a well-scoped R&D consortium that coordinates the activities on a global scale and which works towards openly accessible technologies for the research and industrial product market remains to be established. As with the academic partners, the governing structure should be centred around strong technical involvement of CERN, profiting from existing national and international funding mechanisms and opportunities.