2 High-field magnets

2.1 Executive summary

High-field magnets (HFM) are among the key technologies that will enable the search for new physics at the energy frontier. Approved projects (HL-LHC) and potential future circular machines such as proton-proton Future Circular Collider (FCC-hh) and Super proton-proton Collider (SppC) require the development of superconducting (SC) magnets that produce fields beyond those attained in the LHC. The programme proposed here will advance beyond the results achieved over the past twenty years in past European and international programmes such as EU FP6 Coordinated Accelerator Research in Europe (CARE), EU FP7 European Coordination for Accelerator Research & Development (EuCARD), EU FP7 Enhanced European Coordination for Accelerator Research & Development (EuCARD2), EU FP7 Accelerator Research and Innovation for European Science and Society (ARIES), and current work such as HL-LHC, EU H2020 Innovation Fostering in Accelerator Science and Technology (I-FAST), CERN-HFM and US Magnet Development Program (US-MDP).

Lead times for the development of high-field magnets have a typical duration of a decade. It is therefore important to pursue R&D in parallel with scoping studies for new machines. The development of high-field magnets naturally spans over many fields of science and engineering, requiring a wide range of expertise, and involving strong and coordinated partnership between national laboratories, university and industry. Finally, the development of novel SC magnet technology at the high field frontier requires specialised infrastructure, often of large scale. These considerations mandate a sustained and inclusive R&D programme as a central element of the future European programme, as underlined by the strong recommendations contained in the ESPPU.

The proposed R&D programme has two main objectives. The first is to demonstrate Nb_3Sn magnet technology for large-scale deployment. This will involve pushing it to its practical limits in terms of ultimate performance (towards the 16 T target required by FCC-hh), and moving towards production scale through robust design, industrial manufacturing processes and cost reduction, taking as a reference the HL-LHC magnets, i.e. 12 T). The second objective is to demonstrate the suitability of high-temperature superconductor (HTS) for accelerator magnet applications, providing a proof-of-principle of HTS magnet technology beyond the range of Nb_3Sn, with a target in excess of 20 T. The above goals are indicative, since the decision on a cost-effective and practical operating field will be one of the main outcomes of the development work.

The roadmap comprises three focus areas (Nb_3Sn and HTS conductors, Nb_3Sn magnets, and HTS magnets) enabled by three cross-cutting activities (materials, cryogenics and models, powering and protection, and infrastructure and instruments).

The conductor activities, besides the necessary procurements, will focus on two aspects. Nb_3Sn R&D will push beyond the state-of-the-art to consolidate the critical current capability (target non-copper current density of 1500 A/mm^2 at 16 T and 4.2 K), establishing robust wire and cable configurations with reduced cost. These will then be the subject of a four-year period of industrialisation, which will be followed by a similar period of industrial optimisation. On the HTS side, the intention is to identify and qualify suitable tapes and cables, and follow up with industrial production to ensure the feasibility of large unit lengths (target 1 km) of HTS tapes with characteristics tailored to accelerator magnet applications. This HTS conductor R&D phase is expected to last for seven years.

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The Nb_3Sn magnet development will improve areas of HL-LHC technology that have been found to be sub-optimal, notably the degradation associated with the fragile conductor, targeting the highest practical operating field that can be achieved. The plan is to work jointly with wire and cable development to mitigate degradation associated either with length or electro-thermo-mechanical effects. The R&D will explore design and technology variants to identify robust design options for the field level targeted. The magnet technology R&D will progress in steps over a projected period of seven years, but is intended to provide crucial results through demonstration magnets in time for the next update of the European Strategy for Particle Physics (ESPP). Another five years are expected to be necessary to extrapolate the demonstrator results to full-length units.

R&D plans for HTS magnets focus on manufacturing and testing of sub-scale and insert coils as a vehicle to demonstrate performance and operation beyond the range of Nb_3Sn. Special attention will be devoted to the possibility of operating in an intermediate temperature range (10 to 20 K). The projected duration of this phase of test magnets, i.e. not yet accelerator designs, is seven years. By this time the potential of HTS for accelerator operation will be clear. At least five more years will be required to develop HTS demonstrators that include all the necessary accelerator features, surpassing Nb_3Sn performance or working at temperatures higher than liquid helium.

The cross-cutting technology activities will be a key seed for innovation. The scope includes materials and composites development using advanced analytics and diagnostics, new engineering solutions for the thermal management of high-field magnets, and the development of modelling tools within a unified engineering design framework. We propose to explore alternative methods of detection and protection against quench (especially important for HTS) including new measurement methods and diagnostics. Finally, dedicated manufacturing and test infrastructure required for the HFM R&D programme, including instrumentation upgrades, needs to be developed, built and operated through close coordination between the participating laboratories.

2.2 Introduction

2.2.1 Historical perspective

Starting with the Tevatron in 1983 [1], through HERA in 1991 [2], RHIC in 2000 [3] and finally the LHC in 2008 [4, 5], all recent energy-frontier hadron colliders have been built using SC magnets. These machines made use of a highly optimised alloy of niobium and titanium [6] and it is accepted that the LHC dipoles, with a nominal operating field of 8.33 T when cooled by superfluid helium at 1.9 K, represent the end of the line for the use of this material in a particle accelerator[1].

Near-future and longer-term machines call for the development of SC magnets that produce fields beyond those attained in the LHC [12]. These projects include the high-luminosity LHC upgrade (HL-LHC) [13–16], currently under construction at CERN and collaborating laboratories, and the Future Circular Collider (FCC) design study [17], structured as a worldwide collaboration coordinated by CERN. Similar studies and programmes are ongoing outside Europe, including the Super Proton-Proton Collider (SppC) in China [18]. Significant advances in SC accelerator magnets were driven by past studies such as the Very Large Hadron Collider at Fermilab [19] and the US-DOE Muon Accelerator programme [20, 21]. First considerations of ultra-high-field (20 T) HTS dipoles were fostered by the High-Energy Large Hadron Collider study at CERN [17, 22]. Finally, new accelerator concepts such as muon colliders [23] pose significant challenges for their magnet systems (see also chapter 5). These initiatives provide a strong and sustained motivation for to the development of SC accelerator magnet technology beyond the LHC benchmark.

Having reached the upper limit of Nb-Ti performance, projects and studies are turning to other

[1]Nb-Ti can produce fields well in excess of the LHC dipoles [7–10]. This implies however reduced operating margin, winding current densities that are significantly smaller than in an accelerator magnet, or magnetic configurations that are more effective than a dipole [11].

superconducting materials and novel magnet technology, and encompassing both low-temperature and high-temperature superconductors. It is important to recall the coordinated efforts that have led to the present state of the art in HFM for accelerators. The largest effort over the past 30 years was the development of Nb_3Sn [24] conductor and related magnet technology, with a strong focus at the end of the 1990's by the US-DOE programmes [25–27]. These programmes evolved as a collaboration among the US-DOE accelerator laboratories and associated institutions and continue in consolidated form under the US Magnet Development programme, with the added goal of developing HTS materials and magnets [28, 29]. On the EU side, the first targeted activities were initiated under the EU-FP6 CARE [30] initiative and in particular in the Next European Dipole Joint Research Activity (NED-JRA) [31]. NED-JRA ran from 2004 to 2009 and was followed by the EU-FP7 EuCARD [32]. The main fruit of these collaborations is Facility for Reception of Superconducting Cables (FRESCA2), the dipole magnet that still retains with 14.6 T the highest field ever produced in a clear bore of significant aperture; it is a test facility magnet, designed with a large operating margin and does not include some of the crucial features of a practical accelerator dipole.

HL-LHC is presently the forefront of accelerator magnet technology and construction, with the highest field ever attained at an operating collider. The preliminary results achieved with the 11 T dipoles [33] and QXF quadrupoles [34] demonstrate that Nb_3Sn has the ability to surpass the state of the art represented by Nb-Ti. It is however clear that the solutions used for the HL-LHC Nb_3Sn magnets will need to evolve to improve robustness, industrial yield and cost.

Finally, the interest in the exceptional high-field potential of HTS for many domains of applied superconductivity has also reached accelerator magnets. Cuprates containing either rare earths, i.e. rare-earth barium copper oxide superconductor (REBCO) [35], or bismuth bismuth strontium calcium copper oxide superconductor (BSCCO) [36] are in an early stage of technical maturity and their application to the generation of ultra-high magnetic fields was recently proven. Laboratories and industry have shown that HTS are capable of producing fields from 28 T in commercial nuclear magnetic resonance (NMR) solenoids [37] to 45.5 T in small experimental solenoids in a background field [38]. As discussed later in detail, HTS technology for accelerator magnets is only at its beginning [39]. This is an area where we expect to see fast progress, along the path initiated in various laboratories and fostered in Europe by the EuCARD [32], EuCARD2 [40], ARIES [41] and I-FAST [42] EU projects.

2.2.2 Highest fields attained

The steady increase of field produced by dipole magnets built with Nb_3Sn over the past forty years is summarised in Fig. 2.1. The data is a collection of results obtained with short demonstrator magnets (i.e. simple configurations that lack an aperture for the beam and are not built with other constraints such as field quality), short model magnets (i.e. short version of magnets that are representative of the full-size accelerator magnets) and full-size accelerator magnets.

The first significant attempts date back to the 1980s, at BNL [43] and LBNL [44]. This work eventually led to the achievement of D20, a dipole model with 50 mm bore, in the 1990s [45]. The HD programme at LBNL in the 2000s reached a field of 16 T in the simpler racetrack configuration [46]. Fields in the 16 T range were obtained at CERN [47] in 2015 and exceeded in 2020 [48] in a racetrack configuration, as a result of the push provided by FCC-hh. This body of work [49] laid the foundations for the construction of the HL-LHC Nb_3Sn magnets. The progress shown in Fig. 2.1 is relatively slow. It took about ten years for CERN and associated laboratories [30–32] to reproduce the results obtained in the US.

The conductor R&D initiated in 2004 led to significantly improved powder-in-tube (PIT) conductor [50], with high-field performance comparable to rod-restack process (RRP) conductors, though more sensitive to mechanical loading and with lesser industrial maturity. PIT was used in racetrack model coil (RMC), achieving a field of 16.2 T in 2015 [47] and bringing the EU efforts to a comparable level of maturity with the US. This gives a good benchmark for the time scales intrinsically to this field of technology, including the procurement of the required infrastructure (e.g. heat treatment furnaces, impregnation tanks) and the development of the necessary skills. The result of this work is the record magnet FRESCA2, built in collaboration between CERN and CEA and generating a field of 14.6 T in an aperture of 100 mm diameter [51]. As indicated earlier, FRESCA2 is a test-facility magnet, built with a large operating margin and low engineering current density. This field level has been reproduced recently by the high-field model dipole MDPCT1 built within the US-MDP programme [52] as a step towards the highest field attainable with a cos-theta coil configuration (four layers) and features relevant to an accelerator magnet, including high operating engineering current density.

Finally, the plot shows the remarkable achievement in the development of Nb_3Sn accelerator magnets and in particular the MBH 11 T dipole for HL-LHC built at CERN in collaboration with industry (GE-Alstom) [33]. Initiated in 2010, and profiting from the developments outlined above, it took a decade to produce the first magnet unit. The first magnet, MBHB002, was tested in July 2019 and holds the record for his class [53]. Though successful in achieving the specified performance, the 11 T programme has also demonstrated that there are still questions to be resolved in the long-term reliability of this specific design as well as in the robustness of the manufacturing solutions. These need to be addressed and resolved before this class of magnets can be used in an operating accelerator.

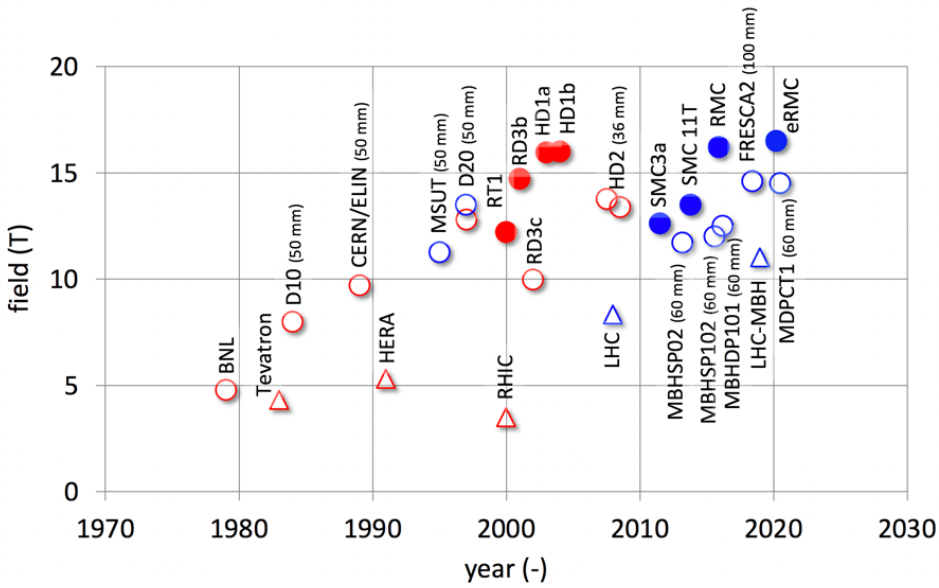

Fig. 2.1: Fields attained with Nb_3Sn dipole magnets of various configurations and dimensions, either at liquid (4.2 K, red) or superfluid (1.9 K, blue) helium temperature. Solid symbols are short demonstrators, i.e. 'racetracks' with no bore, while open symbols are short models and long magnets with bore. For comparison, superconducting collider dipole magnets past and present are shown as triangles.

While Nb_3Sn is the baseline for the high field magnets of HL-LHC, as well as the next step in accelerator magnet technology, significant progress has been achieved recently in HTS technology, reported graphically in Fig. 2.2. The general interest in the potential of this class of material coalesced in the mid-2000s in the EU and US. The US-DOE Very High Field Superconducting Magnet Collaboration [54] targeted BSCCO as an HTS high-field conductor. This activity has now been drawn into the scope of US-MDP [28, 29] which addresses both BSCCO and REBCO in Rutherford and conductor-on-round-core (CORC) cables and various magnet (racetrack and canted cos-theta) configurations [55–57]. In the EU, the first work was within the EU-FP7 EuCARD [32], EuCARD2 [40], and EU-H2020 ARIES [41] programmes. The conductor effort in Europe was directed to REBCO, a conscious choice driven by the perceived potential and presumably simpler magnet technology [39]. The outcomes of these activities are small demonstrator magnets that have reached bore fields from 3 to 5 T in stand-alone mode. Figure 2.2 shows that this is the beginning of a path that will hopefully lead to results exceeding Nb_3Sn. The next step, complementary to the further development of the technology, is to use these small-size demonstrators as inserts in large-bore low-temperature superconductor (LTS) background magnets to boost the central field and quantify the ability to exceed LTS magnet performance, while at the same time exploring this new range of fields and related forces.

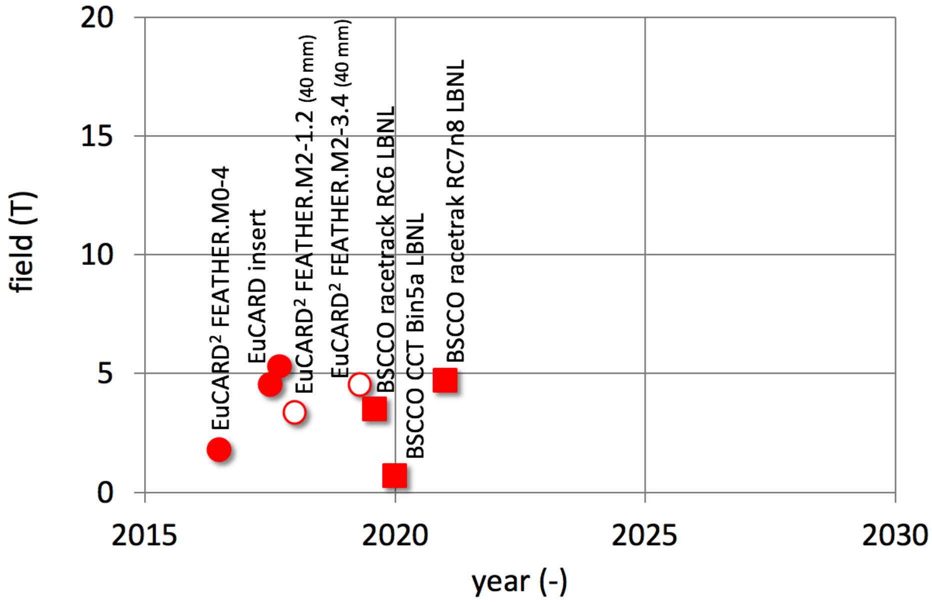

Fig. 2.2: Fields attained with HTS short demonstrator magnets of various configurations, producing a dipole field. All tests performed in liquid helium (4.2 K). Solid symbols are racetrack magnets with no bore, while open symbols are magnets with bore. Round symbols are magnets built with REBCO, square symbols with BSCCO.

2.3 Motivation

Several conclusions arise from the previous section's simplified account of achievements.

- Lead times for the development of high-field magnets are long. The cycle to master new technology and bring novel ideas into application has a typical duration in excess of a decade. It is hence important to pursue R&D in parallel with scoping studies of new accelerators, to anticipate demands and guarantee that specific technology is available for a new facility when the decision to construct is taken.
- The development of novel SC magnet technology at the high-field frontier requires specialised infrastructure, often of large size. The necessary investment is considerable. Continuity is hence important in a programme that requires such investment.
- The development of high field magnets naturally spans over many fields of science and requires a broad mix of competencies, implying a research team assembled as a collaboration across academia and industry. As with the infrastructure, such research teams need investment for their setup and operate most effectively with continuity.

These considerations indicate the need for a sustained and inclusive R&D programme for high-field superconducting accelerator magnets as a crucial element for the future of HEP, reinforced by the strong recommendation made by the European Strategy [58]. Such a programme must respond to the demands of specific projects and studies, but it should also unfold as a continuous line of structured R&D, ready to respond to future requests, and capable of feeding the particle physics programme with opportunities. The programme should include both LTS and HTS materials in a synergistic manner, encompass the spectrum from conductor to accelerator magnets, and include the key technologies necessary for the realisation of its goals. Having dedicated teams established for a period of a decade or more will allow focus and provide results. This matches the timeline of the European Strategy process, with an update in around five years.

The costs of the programme include not only the construction cost of magnets, which is a very significant challenge for future accelerators, but also the cost of the R&D itself, which may tend to limit the scope and stretch the timeline, working against the wish for a fast turn-around. This is especially true for HTS materials, which explains why the scale of the demonstrators described earlier, as well as that of future ones, has been kept intentionally small. The planning of an effective R&D programme must deal with practical considerations of cost.

Given the ambitious scope, the long-term engagement, and the cost, the programme will have to be of collaborative nature, with partnership among national laboratories, universities and industry. The R&D programme should capitalise on the state of the art and achievements obtained so far, continuing the ongoing work presented earlier. An R&D programme with the characteristics outlined is consistent with the plans of other organisations in HEP already mentioned earlier [28,59], as well as other research fields relevant to our discussion [60–63]. Last but not least, it will be important to measure the impact of the R&D programme in other applications in science and society.

2.4 Panel activities

The HFM expert panel has held a series of sixteen meetings. These are collected under an Indico category [64]. Two open international workshops were organised and held virtually:

- 'HFM State-of-the-Art' (SoftA) workshop, that took place from 14–16, 2021 [65];
- 'HFM Roadmap Preparation' (RoaP) Workshop, that took place on 1 and 3 June, 2021 [66].

The workshops included an expert evaluation of the state of the art in HFM for accelerators, topical reviews and technical roadmaps and an overview of the strategic positioning of the main EU actors, including laboratories, universities and industry. The proceedings of the above workshops constitute the main body of the wide and open consultation of the community. The collected inputs were discussed in a restricted roadmap workshop, limited to the panel members, that took place from 15–16, 2021. The proceedings of this workshop are the basis for this report.

2.5 State of the art

2.5.1 Superconductor

The primary challenge in achieving the high magnetic fields of interest for accelerators is to have a conductor with sufficiently high engineering current density (J_e), with good mechanical properties. Based on experience from previous accelerators, a target of $J_e \approx 600$ A/mm^2 at operating field and temperature is appropriate to yield a compact and efficient coil design for an affordable magnet [49]. The J_e target should be reached with no degradation and limited training and making use of the highest possible fraction of the current carrying capacity of the conductor. All known high field superconductors (Nb_3Sn and HTS) are brittle, and it is of paramount importance that the state of stress and strain be controlled throughout all magnet fabrication and operation conditions.

An overview of the state-of-the-art J_e for LTS and HTS technical superconductors is reported in Fig. 2.3. The performances reported there refer to the best industrial products, not necessarily produced in large scale. The LTS materials of interest are Nb-Ti, an industrial commodity, and Nb_3Sn, whose production is restricted to a single established manufacturer for the high-performance wires required by particle physics. On the HTS side, two high-field superconductors are currently available on the market: BSSCO, also produced at a single location worldwide, and REBCO, with several established producers in Europe and worldwide.

In the case of Nb_3Sn the target of J_e can be translated into a minimum critical current density (J_C) in the superconductor of the order of 1500 A/mm^2 at 16 T and 4.2 K [67]. This target, which is a mandatory performance requirement for a compact accelerator magnet, is at the upper boundary of the state-of-the-art best wire performance (see Fig. 2.3) and exceeds by about 50% the performance specified for the industrial production of HL-LHC Nb_3Sn. This implies pursuing and industrialising the R&D work launched in the framework of the CERN FCC Conductor Development programme and undertaken over the last five years on basic material and wire fabrication [68]. Results are encouraging and open the route for novel Nb_3Sn with high in-field electrical performance. In particular, the internal oxidation route has shown the feasibility of exceeding the FCC target in multi-filamentary wires [69, 70].

For HTS, the target J_e is actually common practice for the present production industrial standards of REBCO and BSCCO materials (see Fig. 2.3), so we do not envision a focused effort in the direction of increasing J_C. However, other aspects of the conductor require tailored developments. It is interesting to note that recent developments have demonstrated that the target J_e can be achieved by REBCO at temperatures of 10 to 20 K.

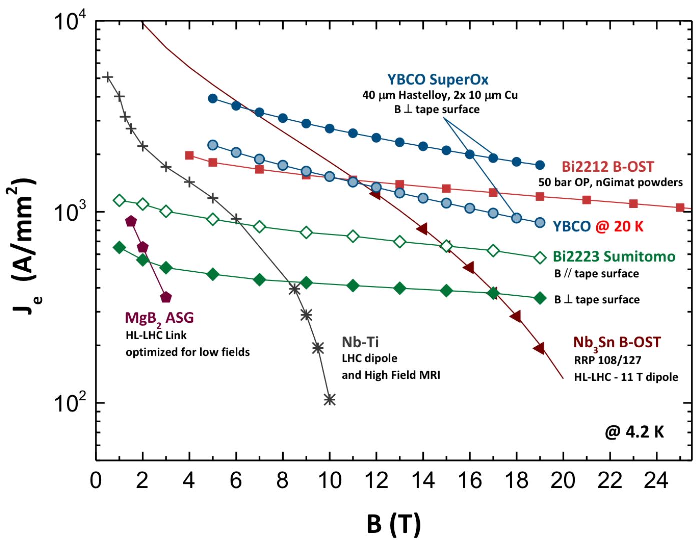

Fig. 2.3: Engineering current density J_e vs. magnetic field for several LTS and HTS conductors at 4.2 K. Latest results for REBCO tapes are reported both at 4.2 K as well as 20 K.

Besides J_e, other performance parameters need to be met for both LTS and HTS. In particular, the mechanical strength and tolerance of wires, tapes and cables to stress and strain is of key importance, specifically to mitigate the risk of brittle fracture under electro- and thermo-mechanical loads. Field quality aspects, and in particular equivalent filament size, for Nb_3Sn and impact of the large width of HTS tapes must be studied. The latter is of key importance for confirming suitability of HTS tape for use in accelerator quality magnets. Finally, quench protection aspects need to be addressed starting at the level of conductor, and then for cables and eventually at the magnet level. While Rutherford cables are the choice for LTS accelerator magnets, high current HTS cables suitable for use in accelerator magnets need to be developed and qualified.

Industrialisation of high-quality conductor for large scale application and its cost are challenges to be addressed for both Nb_3Sn and HTS. Large scale production of conductor would help in the optimisation of the manufacturing processes and therefore reduction of cost. In the development phase, selection of processes and technology must take into account the future requirement for industrialisation. At the time of writing, several manufacturers of HTS tape exist worldwide, in Europe, USA, Korea, Russia and China. However, only one manufacturer to date can produce long lengths of state-of-the-art HL-LHC Nb_3Sn wire. Effort still has to be made to guarantee availability of high-performance Nb_3Sn wire and build up credibility for potential large scale production.

2.5.2 Mechanics

2.5.2.1 Stress and strain in the coil composite

All high-field superconductors are strain- and stress-sensitive and brittle. Besides the known reversible critical current dependency on applied strain, the main concern is that stress or strain exceeding allowable limits for any of the constituents of a wire or tape generally leads to a permanent reduction of critical current and eventual damage through fracture of the superconducting phase. An example of a degradation mechanism is the plastic deformation of the Cu matrix in Nb_3Sn wires, which takes place at moderate stress (range of 150 MPa), and which can freeze a strain state and lead to irreversible J_C reduction. At higher applied longitudinal and transverse stress, the brittle Nb_3Sn can fracture, which reduces the cross-section available to current transport and the wire critical current. Degradation mechanisms for multi-filamentary BSCCO are broadly similar; the Ag resistive matrix has even lower yield strength than a Cu matrix. On layered REBCO tapes, in-plane shear or peeling forces can lead to delamination at stress as low as a few MPa.

Given these considerations, it is paramount to minimise stress concentrations on the conductor. This is why the coils wound from brittle conductor or cable are cast in a matrix material such as glass fibre wraps impregnated with epoxy resin. The fibre increases strength and reduces cracking at cryogenic temperature. The coil becomes a composite material made of conductor, glass and resin. The sources of stress and strain in the coil composite are divided according to their external or internal origin. External sources include the electromagnetic (Lorentz) forces and forces or displacements transmitted at the coil-structure interface. Lorentz forces scale with the magnetic field in the center of the aperture and the ampere-turns, i.e. approximately quadratically with the field in the aperture, as shown in Fig. 2.4. In some quench scenarios, such as quench protection transients with fast current pulses driven by the coupling loss induced quench (CLIQ) system, or in non-insulated or partially insulated coils, Lorentz force patterns may vary significantly from the nominal configuration. Stress and strain transmission at the coil-structure interface is discussed in more detail below in the context of pre-load. We note that tight geometrical tolerances on the coil shape as well as on the structure's interfaces are required in order to avoid local stress-concentration points or excessive overall constraints.

Internal sources of stress are induced by differences in coefficient of thermal expansion (CTE) between the constituents of the coil composite. For example, a differential stress inside the conductor is already present after the heat treatment of Nb_3Sn. More stress is accumulated due to a CTE mismatch between the conductor and the glass-resin matrix during the cool-down from the resin-curing temperature down to cryogenic conditions. The thermal expansion of the coil as a consequence of a quench is the source of additional internal and external stresses, where the internal stresses are due to temperature gradients in the coil and the external stresses are due to the constraint on the coil shape on the boundary.

The local stress and strain in the coil composite follow from the sum of all internal and external contributions. Good engineering requires the knowledge of critical values of stress and strain in the composite to produce a design that implements appropriate safety margins within realistic tolerances. Critical values may vary widely between conductor types and material compositions. Experimental studies and multi-scale modelling are required to establish reliable input into the design workflow. Moreover, for a given central field, the level and orientation of stress and strain in the coil composite varies widely between coil types, coil sizes, materials, and mechanical structures. Indeed, whatever the coil and struc-

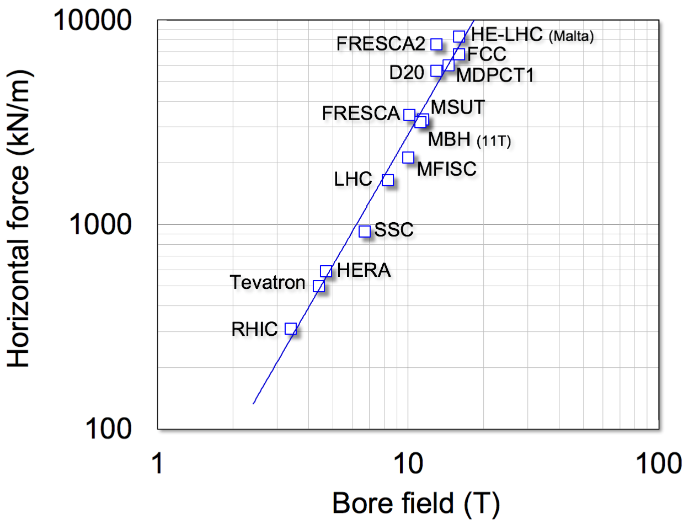

Fig. 2.4: Horizontal forces per quadrant in dipole accelerator magnets (built and tested or design studies).

ture, the status of strain and stress is a tensor. R&D in materials and composites, complemented by full 3D modelling, is mandatory to relate the true mechanical state to the experimental data accessible to measurements.

2.5.2.2 Structures, pre-load and stress management

The transverse and axial forces from the loads identified above are reacted on a stiff internal or external structure, whose aim is to control and minimise the deformation of the coil under Lorentz forces. It is customary to design the mechanical structure so that it applies a coil compression (or pre-load) at cryogenic temperature. This pre-load is introduced to reduce relative movement between the coil and the structure under Lorentz forces. A commonly used design technique is to provide enough pre-load at cryogenic conditions that all interfaces remain in compression up to the ultimate design current. While this is frequently observed in the design phase, it is rarely rigorously applied in R&D practice, especially during the initial magnet assembly and powering. The extent of required pre-load at cryogenic temperature is a matter of debate.

To meet requirements, an external structure must have a CTE identical to the coil composite (to match dimensional change) or higher (to introduce additional load at cool-down). In the case of an external structure made from material with lower CTE compared to the coil, as is the case of several high-strength alloys, the structure can be tensioned, and the coil pre-compressed at room temperature, so that the structure remains in contact with the coil throughout the cool-down. An internal structure may be used to increase the coil's stiffness and to transmit the external structure's stiffness into the inner windings of the coil. An internal structure (often denoted 'stress management') may be a path towards reduced or no pre-load and overall lower coil stresses. It comes at the price of a lower engineering current density and diverse coil-structure interfaces that may be subject to electrical or mechanical failure.

2.5.2.3 Mechanical engineering challenges in magnets

Nb_3Sn magnets. The performance of Nb_3Sn magnets relies upon mastery of the magnet mechanics. This can be quantified by looking at the extent of magnet training (i.e. the number of training quenches required to reach the desired operating current) and the performance retention (e.g. the need for re-training after thermal cycling).

Magnet training is usually assumed to be linked to one or several of the following mechanical phenomena: (1) cracks in the glass-epoxy insulation, (2) resin-metal debonding, and (3) stick-slip movement between the coil and the structure. A performance limitation of mechanical origin, i.e. a failure to reach the design current, may be due to (1) repetitive stick-slip movement, or (2) reduced conductor performance due to excessive stress or strain.

Studies of Nb_3Sn under stress and strain demonstrate relatively low tolerance to mechanical loads. Depending on the specific wire architecture and properties, permanent current reduction due to plastic deformation of the annealed-copper stabiliser starts at around 150 MPa transverse pressure, if applied homogeneously in cryogenic conditions. Filament fracture in these conditions may occur beyond 200 MPa. At room temperature, filament breakage may already happen at 150 MPa. This range of stress is typical of the average pre-load required by high-field Nb_3Sn magnets. It should be underlined that components and assembly tolerances affect the local stress and strain state, resulting in a spread which should be taken into account in the design and manufacturing.

Cyclic loads, be it powering cycles or cool-down/powering/warm-up (CD-PO-WU) cycles, can lead to degradation when a combination of relative movement (due to Lorentz forces and/or CTE mismatch) and friction leave the coil-structure interface in a different state than the original one. Repeated CD-PO-WU cycles may lead to detrimental ratcheting. Repeated quenching may lead to fatigue degradation of the insulation system and quenches could lead to softening if the local temperature approaches the glass temperature of polymer components.

HTS Magnets. HTS coils at low temperature have enthalpy margins up to 100 times larger than those observed in LTS coils. Consequently, energy release and associated training due to cracking, debonding, or stick-slip motion are much less of a concern than in LTS coils. Still, the increased field reach of HTS magnets with respect to LTS ones results in a significant increase of Lorentz force and poses an acute challenge to the composite coil and structural design.

High-strength materials are required to react forces within the relatively compact footprint of an accelerator tunnel. As for the coil composite, any stress concentrations on the HTS wire or tape must be avoided, either by design or via a supporting filler material. In the absence of stress concentrations, REBCO tape will typically withstand very high transverse stress of up to 400 MPa. Much lower values are observed if the stress is localised. At the same time, it has been observed that a CTE mismatch with a filler such as epoxy resin can lead to tape delamination and severe degradation.

Screening currents in REBCO tapes, i.e., non-zero dipolar induced current configurations, can reach high amplitudes in the low-field regions of a coil. Lorentz forces acting on screening currents produce shear and peeling forces, and have been linked to tape deformations and crack propagation in solenoid magnets and need to be considered in the magnet design.

Lastly, coil-wide current-sharing mechanisms such as no insulation (NI), partial insulation (PI), and other advanced-insulation schemes, lead to hard-to-predict current and force patterns in the event of a quench. Such configurations may be exceedingly stable in almost all situations, but also see their mechanical integrity compromised if a quench takes place.

Hybrid magnets. Hybrid LTS+HTS magnets are relevant for cost reasons. All of the above force-related challenges for Nb_3Sn and REBCO coils apply to hybrid magnets. In addition, the Lorentz forces of the insert must be reacted against the external structure via the intermediary of the Nb_3Sn outsert. Some version of an internal structure is likely required to manage the stress on the outsert coil. Moreover, a potentially risky mechanical scenario arises if a quench in one part of the coil is allowed to induce a rise in current in the other part.

2.5.3 *Stored energy and magnet protection*

In Fig. 2.5, we have collected the values of the stored energy per unit length (measured or computed) for a set of existing and conceptual magnet dipoles. The energy stored increases as $B^{2.5}$, consistent with the dependence of energy and field for ideal dipoles. Consequently, aiming at the range of 16 to 20 T, the increase in stored energy with respect to the LHC will be a factor of four to ten, ranging from 1 to 3 MJ/m per aperture. This has implications for magnet design and technology, stemming from considerations of powering (inductance and voltage required to ramp the string of dipoles), as well as magnet protection (energy density and dump time).

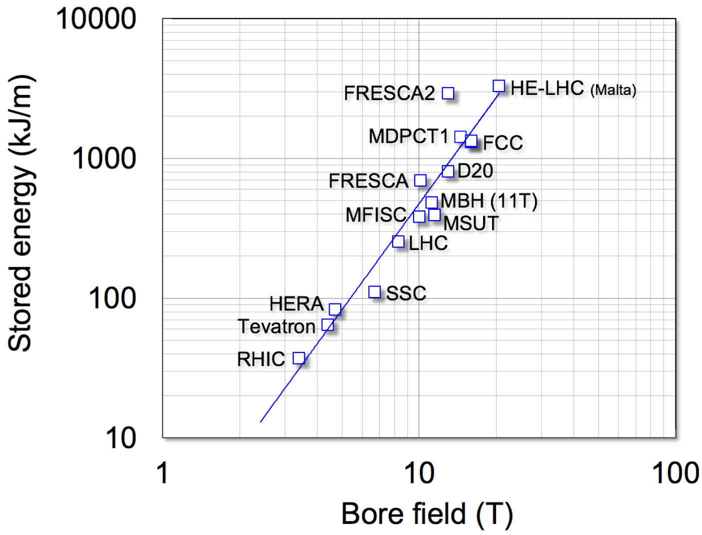

Fig. 2.5: Scaling of stored energy per unit length for dipole magnets built or designed (values refer to one aperture in the case of the LHC, 11 T, FCC and HE-LHC). The line is proportional to $B^{2.5}$

A second element of interest is the energy per unit volume, a main driver for the maximum temperature reached during a quench. As we see in Fig. 2.6, the energy density also increases with field strength. The LHC dipole magnets have a stored energy density of 50 MJ/m^3. This reaches 80 to 100 MJ/m^3 for the HL-LHC Nb_3Sn magnets, and 200 MJ/m^3 for the most compact 16 T FCC designs, i.e. a factor four larger than the LHC magnets.

Considerations of magnet ramping would favour large voltage or current, or a combination of both, to power the magnets of large stored energy. Increasing either terminal voltage or cable current is however not a trivial matter and powering considerations need to be included from the start in the magnet design. Furthermore, in order to keep the hot-spot temperature in the coil after a quench below acceptable values (around 300 to 400 K, but actual damage limits are not well-assessed), the quench detection and active dump need to act at least three to five times faster than in the LHC. This is already challenging for Nb_3Sn, and potentially far harder still for HTS, for which the quench propagation speed is an order of magnitude slower than in LTS and quench detection based on established instrumentation would thus take an order of magnitude longer. In reality, quench initiation and evolution in the case of HTS is a different process to the well-characterised behaviour of LTS. Though relatively unexplored, this may actually be an opportunity to develop alternative schemes, e.g. profiting from the early low voltage quench precursors arising during the current sharing process to anticipate the evolution, or the relatively long time scales of voltage development to improve measurement sensitivity.

The challenges posed by magnet powering and protection have multiple aspects and they need to be addressed in an integrated manner. There is a parallel between the challenges of magnet protection and mechanical design. Firstly, detection and protection in the regime of stored energy and energy density de-

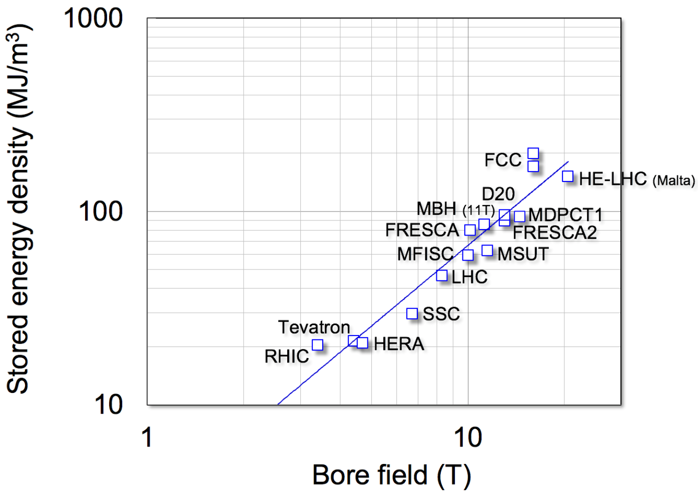

Fig. 2.6: Scaling of stored energy density for the dipole magnets considered in Fig. 2.5

scribed above will require new concepts, especially for HTS (e.g. non-insulated or 'controlled-insulation' windings). Secondly, measurement and characterisation of the thermo-mechanical and dielectric properties and limits of coils and structures will be a mandatory step to ensure that the design is safely within engineering limits.

2.5.4 Cost

Cost is the final challenge for high field accelerator magnets. The main cost drivers and associated opportunities are outlined below.

- The conductor is the primary cost driver for high field magnets. This was already the case for the Nb-Ti based LHC, where the superconductor cost was about 25% of the total cost of the magnet (excluding the external services like power supply and other ancillaries). The cost of Nb_3Sn for an FCC-hh is projected to be half of the cost of the magnet system. Conductor R&D should focus on solutions such as scalable architectures, or designs that are more tolerant of raw material properties, as a route to reducing the cost of the superconductor. Similarly, magnet designs should strive to make the most efficient use of the superconductor cross-section, encouraging engineering solutions that go in this direction.
- The second largest cost is associated with the construction of the coil. Winding is the dominant part, but coil manipulation from winding to coil assembly should not be neglected, especially for Nb_3Sn. In general, magnet design should aim at reducing construction complexity. Coil winding is at present an essentially manually driven operation, assisted by some level of automation[1]. Given the experience gained in coil winding in recent projects (e.g. ITER and JT-60SA) and given the number of coils to be wound for a future accelerator (e.g. 20 000 identical coils for the FCC-hh dipoles) robotics seems a crucial R&D topic to reduce cost. The analysis of benefits of automation and robotics should go beyond coil winding, i.e. coil handling for operations such as insertion in the heat treatment oven, splicing, impregnation, metrology, etc. This work can be staged to take place in a second phase of R&D or in the pre-industrialisation phase.
- The third cost driver is the magnet mechanical structure. The choice among available options

[1]Given the rapid evolution of the field it is not advisable at this stage to heavily invest in robotised tooling, but rather to assess the areas that would benefit. Construction quality and uniformity of production may also benefit, resulting in improved yield and cost reduction. The proposed study should consider the time at which introducing robotisation would be optimally useful.

(e.g. collars, bladders and keys, yoke-as-restraint and others) shall be based not only on field reach, but also on cost consideration of tooling and operation. Some structures seem more suitable to automation and robotisation (e.g. collar assembly), while others rely on simpler tooling (e.g. bladders and keys). The above considerations should be injected early in the magnet R&D study to guide the best structured selection decision when the time comes.

The main challenge can be summarised as finding the true optimum between magnet performance and total cost, not only for the initial investment but also including costs of operation. This tends to favour operation at higher temperatures (e.g. 4.2 K for Nb_3Sn and 20 K for HTS) where, besides the improved cryogenic efficiency, the enthalpy margin is higher and the burden of training is reduced, thus improving availability and reducing operation cost. Similarly, a robust magnet design, with large operating margin, is a way to avoid rejection, increase yield during production, while increasing operating availability, thus reducing both capital and operation cost. Simpler designs should be favoured, built with repeated operations that might be more suitable to automation as described earlier, even if they perform slightly less well. In order to forecast costs correctly, industry should be involved as soon as possible in an efficient manner[2]. Industry involvement can complement laboratory efforts made using existing large facilities. Regardless of industry engagement, it is important that work in laboratories, especially on long magnets, is tracked using a detailed budget accounting system that could be used as a basis to estimate industrial production costs.

HTS optimisation is quite different from Nb_3Sn and deserves a special mention. HTS conductor cost is currently much higher than Nb_3Sn. However, contrary to Nb_3Sn, HTS price is decreasing, driven by demand and steady funding from fusion research (in particular two privately funded initiatives in EU and US) and the energy sector. Appreciable material quantities, far exceeding particle physics needs, are in order to satisfy the needs from these initiatives. In this respect, high energy physics (HEP) should rather focus on cable and magnet engineering, leaving the cost of superconductor aside, at least in this phase.

Concerning magnet construction and operation, depending on the HTS material (REBCO) there is no need of heat treatment. Mechanical properties are better and stability much higher than LTS. Considering this, HTS magnet technology could at some point be significantly less expensive than Nb_3Sn. This needs to be verified since it could lead to a change in paradigm for a FCC-hh or a muon collider, should the cost of HTS conductor attain the same level as Nb_3Sn. These considerations can be included in the R&D programme; as well as the step-by-step validation of the technology, it is important to include a near-full size HTS dipole (1 m long) to be manufactured and tested. This will allow an assessment of the true cost of an HTS accelerator magnet by tracking material and personnel investment throughout the construction process. A suitable target for one such magnet could be a typical HL-LHC model magnet size and field (e.g. 50 to 60 mm aperture, field in the 11 to 12 T range) for which cost is well established.

2.6 R&D objectives

2.6.1 Technical goals

Based on the current state of the art and the challenges described above, the following are the long-term technical goals of the HFM R&D:

1. Demonstrate Nb_3Sn magnet technology for large scale deployment, pushing it to its practical limits in terms of maximum field and production scale. The drivers of this first objective are to exploit Nb_3Sn to its full potential, developing design, material and industrial process solutions that are required for the construction of a new accelerator based on this technology. We separate the

[2]We believe that industry will consider an involvement seriously only if: (a) there is continuity of work and funding, since industry needs to make plans with at least five years horizon to be effective; (b) the issue of IP is clarified, since it is unlikely that industrial IP will be available if issues protection and sharing are not settled from the start.

search for maximum field from the development of accelerator-magnet technology by defining the following two dependent sub-goals:

(a) The effort to quantify and demonstrate the Nb_3Sn ultimate field comprises the development of conductor and magnet technology towards the ultimate Nb_3Sn performance. The projected upper field limit for a dipole is presently 16 T (the reference for FCC-hh). This field is the target against which the performance of a series of short demonstration and model magnets should be measured.

(b) Develop Nb_3Sn magnet technology for collider-scale production, through robust design, industrial manufacturing processes and cost reduction. The present benchmark for Nb_3Sn accelerator magnets is HL-LHC, with an ultimate field in the range of 12 T and a production of the order of a few tens of magnets. Nb_3Sn magnets of this class should be made more robust, considering the full spectrum of electro-thermo-mechanical effects and the processes adapted to an industrial production on the scale of a thousand magnets. The success of this development should be measured through the construction and performance of long demonstrator and prototype magnets, targeting the 12 T range.

2. Demonstrate the suitability of HTS for accelerator magnet applications providing a proof-of-principle of HTS magnet technology beyond the reach of Nb_3Sn. The goal of this programme is to break from the evolutionary changes of LTS magnet technology, from Nb-Ti to Nb_3Sn, by initiating a revolution that will require significant innovation in materials science and engineering. A suitable target dipole field for this development is 20 T, significantly above the projected reach of Nb_3Sn. Besides answering the basic questions on field reach and suitability for accelerator applications, HTS should be considered for specific applications where not only high field and field gradient are sought, but also higher operating temperature, large operating margin and improved radiation tolerance.

In addition, it is also important to underline that the HFM R&D programme is intended as a focused, innovative, mission-style R&D in a collaborative and global effort, targetting specific results relevant to future accelerators, with well-defined timeline, deliverables and milestones, and paying special attention to novel engineering solutions.

The main objectives are represented in Fig. 2.7, where we plot the length of dipole magnets produced (i.e. magnet length times the number of magnets) versus the bore field. The blue line gives an idea of the state of the art, bounded on one side by the nearly 20 km of Nb-Ti LHC double-aperture magnets in the range of 9 T ultimate field and at the high-field end by single model magnets with approximately 1 m length and 14.5 T maximum field. The HL-LHC point marks the production of 6 dipoles of 5.5 m length with 12 T ultimate field. The objectives listed above can be represented in this plot as an extension of the field reach by moving along the horizontal axis (magnetic field) thanks to advances in Nb_3Sn and HTS magnet technology, as well as an extension of the production capability by moving along the vertical axis (magnet length) thanks to the development of robust and efficient design and manufacturing processes. The symbols at higher field (Nb_3Sn at 16 T, HTS at 20 T) and longer magnet length (5 km) represent targets, providing the desired R&D direction and they should not be read as specified performance.

The parallelism in the development is an important aspect of the programme. We believe this is necessary to provide significant advances towards the long-term goals within a five to seven year time frame, i.e. responding to the notion of mission-style R&D that needs to feed into the next update of the European Strategy for Particle Physics.

The graphical representation of Fig. 2.7 discussed above only defines the first phase in the R&D from 2021–2027. Once it is proven that the field reach can be extended and the actual level is demonstrated, we foresee a follow-up phase. This should occupy 2027–2034, and will prove the new generation of high field magnets at a scale of accelerator-magnet prototype, i.e. several meters of total magnet length. This is represented by the green arrow in Fig. 2.7, whereby the choice of the field level, and the actual

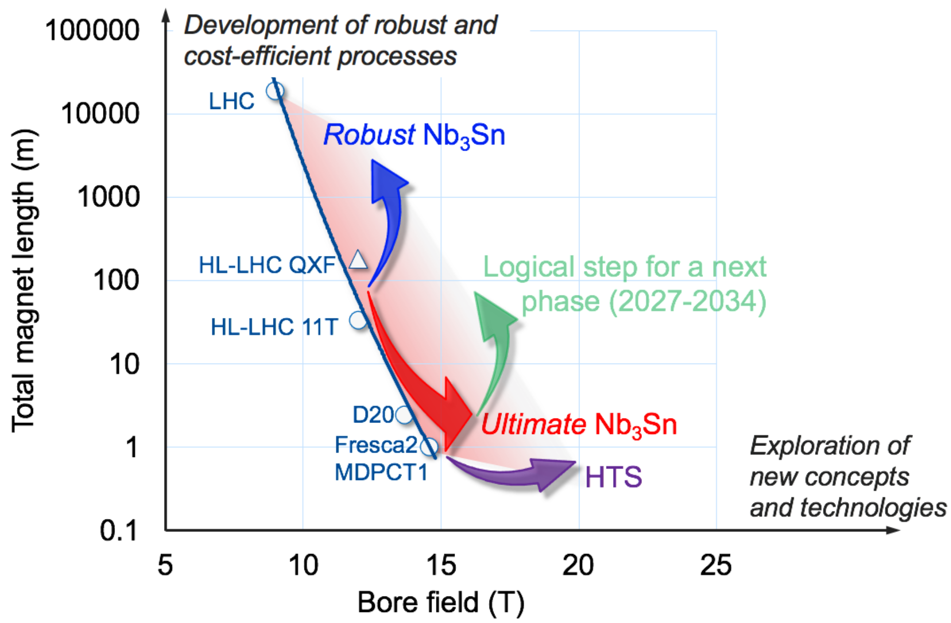

Fig. 2.7: Graphical representation of the objectives of the HFM R&D programme from 2021–2027. Both fronts of maximum field (red for Nb_3Sn, purple for HTS) and large-scale production (blue) will be advanced. Also represented, in green, is a possible evolution for the longer term, 2027–2034.

magnet length to be realised are again only indicative, and will depend on the results of the first phase of R&D.

The R&D targets respond directly to the demand of principal stakeholders. The HFM R&D targets formulated for Nb_3Sn magnets stem directly from the requirements of FCC-hh [17], and are compatible with the schedule of an integrated FCC programme [71]. The parallelism proposed has the advantage that it will provide early results for a decision on magnet technology towards the construction of the next hadron collider.

It is also recognised that the development of capture, cooling, acceleration and collider magnets for a muon collider [23] remains a formidable task. This will be addressed by targeted studies, but the R&D on high-field Nb_3Sn and HTS magnets will be highly relevant in developing suitable solutions. Examples are: (a) HTS conductor and coil winding technology towards a 20 T goal, including partial- and no-insulation windings, whose results could be applied to the ultra-high-field capture solenoids, or to the high-field collider magnets; (b) the study of stress management in Nb_3Sn magnets towards their ultimate performance, directly applicable to large aperture dipoles and quadrupoles for the high-energy muon collider main ring and interaction region (IR)—see e.g. Section 5.6 (in particular Tables 5.2 and 5.3); and (c) HTS magnet operation at temperatures above that of liquid helium, relevant to operation in the high heat load and radiation environment of the muon collider ring—see e.g. Section 5.6.5.

2.6.2 *Programme drivers*

To define the work necessary to meet the objectives above, a number of practical questions can be prioritised. These questions are the R&D programme drivers, and they can be broadly divided into questions of relevance for Nb_3Sn, for HTS, and common to both lines of development.

For Nb_3Sn, taking into account the pioneering developments already in place:

- Q1: What is the practical magnetic field reach of Nb_3Sn accelerator magnets, driven by conductor performance, but bounded by mechanical and protection limits? Is the target of 16 T for the ultimate performance of an affordable Nb_3Sn accelerator magnets realistic?
- Q2: Can we improve robustness of Nb_3Sn magnets, reduce training, guarantee performance retention, and prevent degradation, considering the complete life cycle of the magnet, from manufacturing to operation?
- Q3: Which mechanical designs and manufacturing solutions, including basic materials, composites, structures, and interfaces need to be put in place to manage forces and stresses in a high-field Nb_3Sn accelerator magnet?
- Q4: What are the design and materials limits of a quenching high-field Nb_3Sn magnet, and which detection and protection methods need to be put in place to remain within these limits?
- Q5: How can we improve design and manufacturing processes for Nb_3Sn accelerator magnets to reduce risk, increase efficiency and decrease cost for industrial production on large scale?

For HTS high-field accelerator magnets, the questions are more fundamental to the potential and suitability for accelerators, with the awareness that the body of work in progress is not yet at the point where a reference technology can be defined:

- Q6: What is the potential of HTS materials to equal and surpass the present and projected limits of Nb_3Sn, and in particular is the target of 20 T for HTS accelerator magnets realistic?
- Q7: Besides magnetic field reach, is HTS a suitable conductor for accelerator magnets, considering all aspects from conductor to magnet and from design to operation?
- Q8:What engineering solutions, existing or yet to be developed and demonstrated, will be required to build and operate such magnets, also taking into account material availability and manufacturing cost?

Finally, common to Nb_3Sn and HTS:

- Q9: What infrastructure and instrumentation are required for successful HFM R&D, taking into account aspects ranging from applied material science to production and test of superconductors, cables, models and prototype magnets?
- Q10: What is the quantified potential of the materials and technologies that will be developed within the scope of the HFM R&D programme towards other applications to science and society (medical, energy, high magnetic field science) and by which means could this best be exploited?

2.7 Delivery plan

2.7.1 Innovation through a fast-turnaround R&D programme

The HFM R&D Programme must achieve decisive progress in the three areas of performance, robustness, and projected cost. This applies in principle to both Nb_3Sn and HTS magnets, though different weights will be put on each aspect. Any technology demonstration should meet the required goals in each of the three areas, though finding the right balance between cost-efficiency, maximum field, and robustness may imply some compromises. The specification of the three areas will need to consider the following issues:

- Performance consists not only of attaining the required central field strength, with swift training exhibiting no performance limitation, but also in retaining such performance, and in particular preventing degradation under all foreseeable operating conditions including quenches and repeated thermal cycles. A crucial element of performance is a successful quench detection and protection strategy, avoiding overheating or electrical breakdown. Finally, the field quality demanded for accelerator operation, and an efficient thermal management are important performance indicators of a specific design and technology

- Robustness covers several aspects of magnet design and manufacturing, and revolves mainly around the engineering knowledge and margin of a specific technology. Going beyond the present focus of robustness, driven by considerations of magnet performance retention, we measure its effectiveness by looking at the scalability of a given technology both in terms of length and units. This implied a wider acceptable range of material and component tolerances, suitability for automation, improved reproducibility and a high yield of conforming coils and magnets.
- A cost target will be defined based on a projected accelerator-scale production. Having such a target will be helpful to influence and steer design, process and material optimisation.

The R&D programme must be holistic in nature: a compatible selection of electromagnetic, mechanical and thermal design approaches, conductors, materials, and manufacturing processes and methods needs to be integrated seamlessly with instrumentation and protection into a specific magnet solution responding to the required specification. Various such selections are possible, and although an absolutely objective comparison of technical solutions is difficult, starting from a unique design basis allows for a fair technology selection. In this context, it is important that sufficient time and resources are allocated to ensure that all developments are thoroughly tested and analysed.

Despite the broad existing body of knowledge in accelerator magnet technology, we believe that demonstrating ultimate performance will require innovation beyond the state of the art in most areas. This, in turn, will call for a period of basic technology R&D, followed by a multi-year magnet design, construction and testing process, with duration from three to four years. In a serialised program, the experimental feedback would come late in the process, likely too late for substantial changes to the selected technologies. Only a few iterations could be implemented and tested within the available timeline, with minor tweaks and improvements. We conclude that the innovation potential of this approach is limited due to the slow turnaround.

This reflection leads to a third characteristic element of the R&D Programme. We propose to structure the magnet R&D as a succession of meaningful fast-turnaround demonstrations, ranging from non-powered material and composite samples, to powered sub-scale samples and mechanical models, to racetrack coils and/or demonstrator coils in short and long mirror configurations, to accelerator magnet demonstrators at intermediate fields and, eventually, towards ultimate specifications. In this way, new technologies can be tested under realistic conditions at the earliest possible stage, the smallest relevant scale and cost, and the fastest pace.

We represent this process schematically in Fig. 2.8. The different levels of the pyramid represent the stages of an innovation climb, providing means for a constant bi-directional stream of feedback between technology and magnet R&D. In this scheme, technology R&D does not stop once the first demonstrator magnet is designed. Demonstrations can go through steps of increasing performance (and complexity). The most efficient technologies naturally rise to the top of the pyramid in due time and are implemented when judged mature. Access to testing infrastructure of course becomes a particularly important issue when planning for multiple multi-scale fast-turnaround R&D programmes. Multiple tests provide opportunities for the application of novel instrumentation to be developed in the HFM program. To make full use of this opportunity, timely data analysis is vital and requires dedicated resources.

For the programme to remain focused, it is important that all technologies developed, and all demonstrators built, are compatible with the ultimate design specifications. Only then can a success in the experimental results at a smaller scale be translated into a credible statement on the technical and financial feasibility of ultimate specification magnets. We suggest that, for this purpose, each magnet R&D programme accompany their multi-scale R&D from the earliest days with an evolving ultimate-specification conceptual design that is regularly updated in the light of the most recent developments and

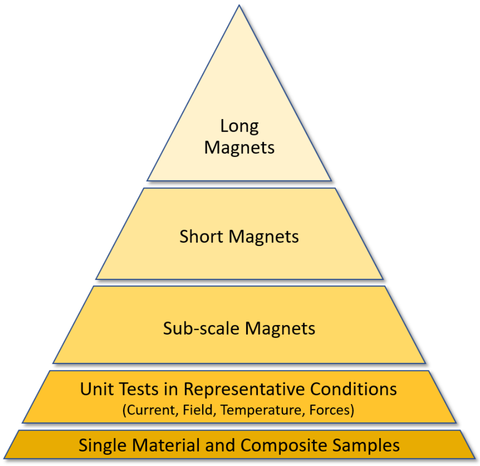

Fig. 2.8: Schematic representation of the innovation pyramid concept, supporting fast turnaround technology development.

experimental results. It is understood that the HFM programme will extend far beyond the immediate five-year period, and will extend to double-aperture magnets as well as long magnets in the years following the next ESPPU. For long magnets, a logical first step in the scale-up to 15 m is the maximum length that can be tested in vertical or horizontal bath cryostats.

Using this approach, each contributor to the R&D programme can profit from a number of specific R&D vehicles, focusing on a selected subset of the ultimate specifications mentioned above. As an example, some R&D teams may place their initial focus on the demonstration of technologies for enhanced robustness at lower cost, others may aim towards innovations enabling higher performance targets. Such a complementary approach, carefully coordinated among all actors, can achieve the parallelism that is key to swift advancement.

In practice, it is likely that some national or institutional programmes will seek to build upon the wealth of experience from previous programmes, such as the EU R&D initiatives and the HL-LHC magnet construction, and opt for an evolutionary approach. Others will pursue a more radical departure from the state of the art. The overall HFM programme must have a balanced approach risk, maximising the chances of overall success on a broad front. Eventually, the results from all studies will inform a single coherent and evidenced position, such that the combined results constitute the required demonstration of technical and financial feasibility of the magnet system for a future collider. To enable this, the HFM programme shall foster a structured exchange among magnet engineers from all laboratories to coordinate their efforts and discuss their respective challenges. Moreover, the programme shall ensure a regular exchange between researchers in other R&D areas, so that engineers can communicate their most pressing technological needs, while receiving creative input from technology specialists across all participating institutes. These structured meetings shall trigger further informal exchanges resulting in interdiscplinary joint research embedded in a vibrant R&D network.

2.7.2 Programme structure

The structure of the programme is represented graphically in Fig. 2.9. We have identified three focus areas, in foreground, covering the R&D work specific to: (a) Nb_3Sn magnets; (b) HTS magnets; and (c) Nb_3Sn and HTS conductors. Activities in these areas comprise deliverables and milestones consisting either of demonstrators and critical decisions (e.g. field reach of the magnet technology) or of specifications (e.g. for superconductor procurement). Work in the focus areas will be supported by three cross-cutting R&D activities: (a) structural and composite materials, cryogenics and thermal management, and modelling; (b) powering and protection; and (c) infrastructure for production and test as well as instruments for diagnostics and measurement. The cross-cutting activities are intended to proceed in the background, responding to the challenges identified by the focus areas and supporting the programme in its progression towards the main deliverables. An indicative overview of activities in the form of a top-level timeline is shown in Fig. 2.10. The dates shown in the *'Top-level milestones and deliverables'*—Sections 2.7.3.3 through 2.7.9.3—are necessarily indicative, as they are resource and progress dependent.

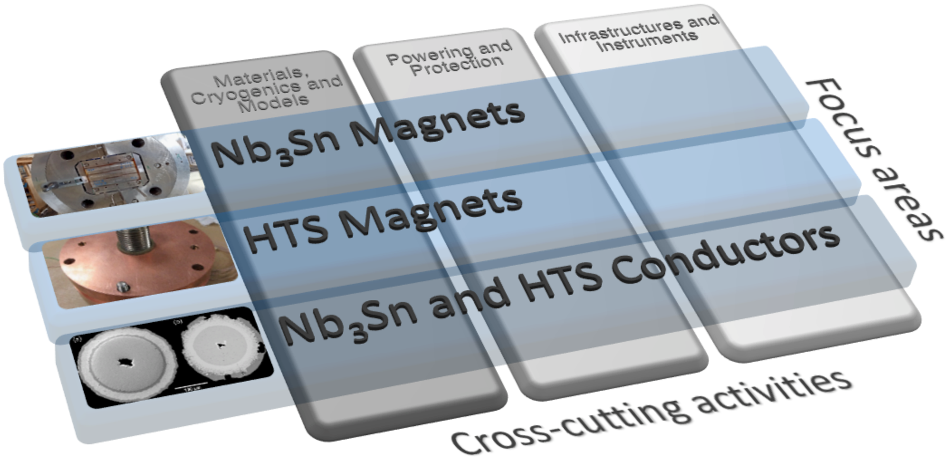

Fig. 2.9: Schematic representation of the structure of the proposed programme, consisting of three focus areas pursued with the support of cross-cutting activities.

2.7.3 Nb_3Sn conductor

2.7.3.1 Scope and objectives

The Nb_3Sn conductor R&D has two main goals: (a) to advance performance of Nb_3Sn wire beyond present state of the art, and (b) to consolidate performance and ensure industrial availability of state-of-the-art HL-LHC Nb_3Sn wire. The necessary performance corresponds to the full set of requirements, including manufacturing, electrical, magnetic and mechanical properties as well as cost, specified for the FCC Conductor Development programme [67]. R&D is still needed to achieve these targets, which will require seven to ten years, with significant results from the R&D work during the first five years.

A key objective will be to develop optimised manufacturing processes for enhancing J_C to the target 1500 A/mm^2 at 16 T and 4.2 K [68]. The methodologies proven to reach J_C at laboratory scale need to be scaled up, in parallel with study of electromagnetic stability, e.g. achieving high enthalpy margin, and improvement of the mechanical properties of the novel wires and cables as a mitigation of the brittle nature of Nb_3Sn and degradation risk. These studies are mandatory to exploit the full J_C potential.

The experience from the CERN FCC Conductor Development programme is that R&D activity in laboratories is a prime source of innovation in materials [69, 70], especially when control and analysis of properties at the nanoscale are needed. Novel concepts have been generated in laboratories, whose agility and focus have proven crucial for the initial R&D phase. Work in industry, however, must start at an early stage to enable identification technologies that have potential for industrialisation. This will be pursued via the production of novel wires, and through studying the feasibility of large billets for large-scale production. This is a key step towards cost reduction, with a goal of 5 €/kAm at 16 T and 4.2 K.

The development of Rutherford cables is included in this activity, as well as extensive measurement of their electro-mechanical performance. The reference targets for successful cabling are a critical

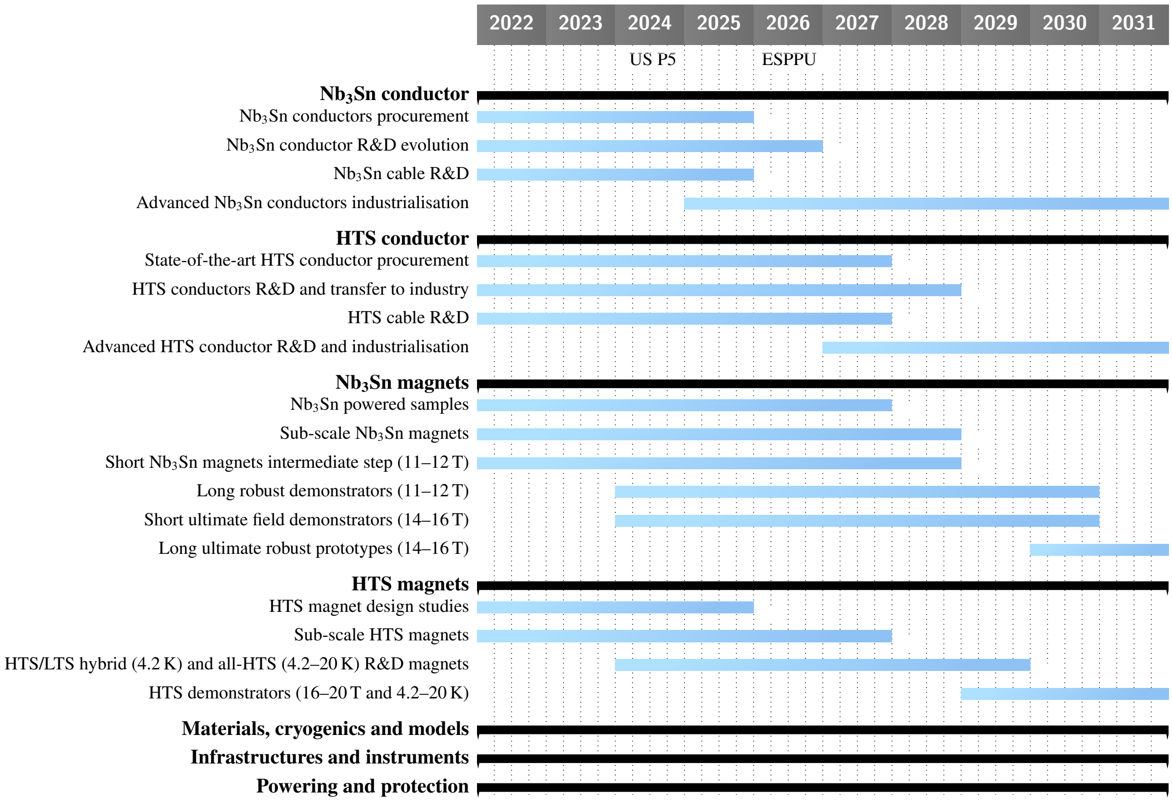

Fig. 2.10: Indicative timeline of HFM R&D activities.

current degradation of the wire in the cable of less than 5% and retention of the stabiliser resistivity ratio above 100. The study of mechanical stability and windability for use in coils is of particular relevance, especially for wide cables with high in-field current capability, including the optimisation of their electro-mechanical performance. The latter shall include the impact of impregnation process. The activity will be naturally interacting closely with Nb_3Sn magnet developments.

Similarly, development and qualification of low-resistance splices between LTS cables, both in low and high fields, are essential to enable high-field magnet designs, and to simplify and increase robustness of the manufacturing process. This study will also require tight interaction with Nb_3Sn magnet R&D.

2.7.3.2 Identified tasks

- **MAG.LTSC.SOAP**: Procurement of Nb_3Sn wires in industry, cable manufacturing, and qualification of wires and cables as required by the magnet programme. The initial phase will be based on state-of-the-art specifications (HL-LHC).
- **MAG.LTSC.COND**: Development and characterisation of novel Nb_3Sn wires with improved performance beyond the state of the art, towards robust high-J_C wires. This effort explores materials and architectures via effort in laboratories and industry, and interacts closely with magnet development to integrate electro- and thermo-mechanical results in relevant geometries and conditions.
- **MAG.LTSC.CABL**: Development and characterisation of cables using novel wires and geometries (e.g. large number of strands). This activity includes study and qualification of electrical, magnetic and mechanical properties as well as iteration with the magnet designers to quantify cable wind-ability for different coil layouts.
- **MAG.LTSC.ADVP**: Evolution of the procurement activity in the direction of advanced wire composition and architecture, as a result of the wire R&D activity, including an effort to enlarge the

industrial manufacturing base.

2.7.3.3 Top-level milestones and deliverables

- **MAG.LTSC.M1**: Launch procurement of state-of-the-art Nb_3Sn conductor, Q1 2022.
- **MAG.LTSC.M2**: Launch development of novel Nb_3Sn wires, Q1 2022.
- **MAG.LTSC.D1**: ~2 tons of cabled and qualified state-of-the-art conductor, Q4 2023.
- **MAG.LTSC.M3**: Assess feasibility of targets for production of at least 100 m unit lengths of novel wires, Q3 2024.
- **MAG.LTSC.D2**: Advanced Nb_3Sn wire in unit lengths of about 100 m, Q1 2025.
- **MAG.LTSC.M4**: Assess results from R&D and update performance of HFM reference wire, Q2 2025.
- **MAG.LTSC.M5**: Industrialise novel wires, Q1 2025.
- **MAG.LTSC.D3**: Novel generation of cables in unit length of at least 100 m, Q4 2025.

2.7.4 HTS conductor

2.7.4.1 Scope and objectives

R&D on HTS conductor is considered essential for a subsequent successful implementation of HTS coils and magnets. The first objective is the definition of performance targets adapted to accelerator magnet applications, which will guide the development. We propose that activities in Europe are focused on REBCO tapes. The reason, as mentioned earlier, is that very high in-field electrical performance is already available in commercial REBCO tapes, with upper values of industrial production reaching J_e (4.2 K, 20 T) up to 2000 A/mm^2 (see Fig. 2.3) [72]. Material engineering at the nanoscale and artificial pinning techniques are well controlled, and several industrial suppliers on the market are able to produce unit lengths of tape of several hundred meters.

Given the exceptional state-of-the-art values of J_e, the R&D work should focus on achieving controlled, homogeneous and reproducible electro-mechanical and geometrical properties along the full tape length, e.g. low internal electrical resistance between layers, high internal adhesion strength among layers, low electrical resistivity of the copper stabiliser, and controlled geometry. Innovation will be required for designing and qualifying novel high-current cables made from tape conductor. This study must be performed in conjunction with the design of HTS magnets and with understanding of their requirements.

The results of this work will provide direct feedback to industrial manufacturers, raising their awareness of needs, identified problems and potential solutions. Industry will be crucial in the demonstration of feasibility of long lengths and low cost. Indeed HTS cost reduction is mandatory to make future large-scale applications affordable. Some routes towards cost reduction may be process optimisation, use of new technology, and production scale-up. We remark here that the scale of production needed for HTS accelerator magnet R&D will not be sufficient to significantly influence cost. However, we will benefit from relatively large ongoing procurement of HTS conductor by other communities, e.g. fusion and energy.

Finally, a crucial aspect of the HTS conductor R&D will be the identification, development and qualification of cable configurations suitable for accelerator-quality magnets, taking into account a possible evolution of the needs of beam dynamics. Existing cable concepts (e.g. stacks [73,74], CORC [75], Roebel [76], stacked tapes assembled in rigid structure (STAR) [77]) and alternative novel concepts will be studied, considering their electro-dynamic performance (e.g. the need for transposition), quench detection and quench protection (to be addressed at the level of tapes and cables before coils), the effect of insulation and impregnation, and the development of low-resistance joints (with procedure scalable to magnet construction). As for Nb_3Sn, HTS conductor development and qualification will have to act in synergy with the R&D on magnets.

2.7.4.2 Identified tasks

- **MAG.HTSC.SOAP**: Procurement of REBCO tapes in industry, qualification and extensive characterisation of electro-mechanical properties, including response to quench.
- **MAG.HTSC.COND**: Development of REBCO tapes with improved performance beyond the state-of-the-art, tailored to accelerator applications. R&D on other HTS materials, including multi-filamentary HTS wires.
- **MAG.HTSC.CABL**: Conceptual development, assembly and extensive characterisation of REBCO cables for use in HTS magnets. Development of splice technology at the level of the tape and cable, suitable for integration in HTS magnets.

2.7.4.3 Top-level milestones and deliverables

- **MAG.HTSC.M1**: Launch procurement of HTS conductor, Q1 2022.
- **MAG.HTSC.M2**: Review performance of REBCO tape for accelerator magnets, Q4 2023.
- **MAG.HTSC.M3**: Select cables' layout for winding magnet demonstrators, Q3 2024.
- **MAG.HTSC.D1**: $\sim$20 km of qualified tape (12 mm equivalent width) by Q1 2025.
- **MAG.HTSC.D2**: Unit lengths of representative cables ($\sim$50 m) by Q1 2025.

2.7.5 Nb_3Sn magnets

2.7.5.1 Scope and objectives

Nb_3Sn magnet R&D is the most prominent cross-cutting, and integrated activity in the proposed programme. The scope of this activity corresponds directly to the ESPPU recommendation to "investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV". This goal translates into a major push to provide robust and cost-effective magnet performance near the ultimate limits of Nb_3Sn superconductor.

Performance is defined in terms of a maximum field in the magnet aperture, a high initial training quench with few training quenches up to ultimate field, and the absence of degradation under cyclic load and repeated cool-down/powering/warm-up cycles. Appropriate electro-mechanical margins need to be implemented, for which the community habitually uses 'margin on the loadline', as well as a generic mechanical design limit for the coil composite of 150 MPa von Mises stress at room temperature and 200 MPa von Mises stress under cryogenic conditions. To mitigate the risks of excessive training, critical current reduction, and degradation, we suggest in the medium term to re-define appropriate engineering margins based on local stress-strain states in the conductor and composite, and to establish a multi-scale framework of experimental results and numerical models that inform the design process.

Robustness is defined based on scalability of the technology, i.e. a technology that works equally well for short magnets and 15 m long magnets, and can be applied at an industrial scale with high production yield. Present experience shows that scaling up the length may come with challenges related to deformation and residual strain in the coil after heat treatment and to the differential contraction mismatch of individual magnet components during cool-down. Due to the strain sensitivity of Nb_3Sn, this mismatch can lead to conductor degradation. Moreover, the magnet production for HL-LHC shows that the yield and methodology are not yet suitable for upscaling, and require a decisive improvement.

Cost relies critically on economies of scale and on the introduction of industrial processes that will include the automation of specific process steps. Neither economies of scale, nor the automation of process steps will be achievable in the present project period. Nonetheless, every design choice and process development must consider the potential impact on cost and the prospect of future automation.

Finding the right balance between cost efficiency, maximum field, and robustness is at the core of this R&D activity, and progress in all three areas is crucial to provide satisfactory input into the next ESPPU.

This progress is likely not going to come from a merely evolutionary change of existing Nb_3Sn technology. Rather, it will be the product of a vigorous innovation and R&D programme that involves all other activities described in this document. Fast turnaround testing at the smallest possible scales is key to an effective innovation funnel that may enable decisive breakthroughs in performance, robustness, and even cost. To this end, we propose to structure the program as outlined in Fig. 2.11, by making use of the development vehicles described below.

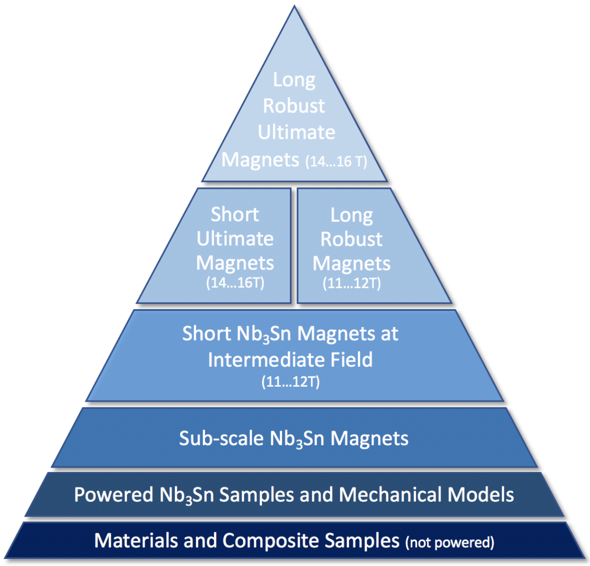

Fig. 2.11: Schematic representation of the technology pyramid towards the development of Nb_3Sn ultimate dipole magnets. The first tasks are shared, then two final objectives are pursued in parallel: on the left, the path towards ultimate-field Nb_3Sn accelerator magnets; on the right, the path towards long Nb_3Sn robust accelerator magnets, eventually joining in the final objective of highest practical field with robust performance.

- Non-powered standardised samples for electrical and thermo-mechanical characterisation. The samples will be developed jointly with the conductor development activity, aiming at material and composite properties, validation tests for new technology variants, and design parameters. Work on these samples goes hand in hand with the cross-cutting activity on material testing.
- Powered samples, testing at the smallest possible scale at which the challenges of HFM can be addressed and studied, e.g. cable degradation, bonding and sliding properties, techniques for reliable jointing of SC cables, etc.
- Sub-scale magnets, which constitute a first step in magnet technology implementation, identifying strengths and weaknesses of specific technology integrated in a coil winding. A sub-scale magnet aims at reproducing the performance margins, but not the main field, in a small (essentially hand-held) magnet assembly. New conductors can be validated at this scale (e.g. designs resilient against degradation).
- Short magnets, which are a true representation of magnet design and construction except for the

length, are a mandatory demonstration step before long magnets. It is likely that short magnets will be built with two coil layers/decks first, aiming for 12 T in the aperture. This step is followed by an ultimate performance design. The short magnet scale R&D will benefit from the faster turnaround of mirror configurations in the early stages of the programme.

- Long magnets, which demonstrate the suitability of a technology in terms of length scale-up. Special attention is paid at this stage to the prospect of industrialisation and automation. Mirror configurations, as well as cool-down/warm-up cycles with dummy coils can be a valuable tool to intercept difficulties at the earliest possible stages.

2.7.5.2 *Identified tasks*

We define here tasks on the basis of a single development site (laboratory). Tasks of sample measurements are likely to be shared among laboratories, while demonstrator tasks will run in parallel to cover the respective design and technology variants selected.

- **MAG.LTSM.SMPL**: Sample construction, test and evaluation. We include in this activity non-powered samples as well as powered samples and mechanical models representative of magnet conditions.
- **MAG.LTSM.SUBS**: Construction, test and analysis of sub-scale magnets.
- **MAG.LTSM.SD12**: Design, construction, test and analysis of short 12 T demonstrator magnets as an intermediate step towards ultimate performance, and to develop robust designs.
- **MAG.LTSM.SD16**: Design, construction, test and analysis of short ultimate-field Nb_3Sn demonstrator magnets.
- **MAG.LTSM.LD12**: Design, construction, test and analysis of long 12 T demonstrator magnets.

The ultimate goal, long robust dipole magnets at ultimate performance is beyond the horizon of the next European Strategy Update.

2.7.5.3 *Top-level milestones and deliverables*

In the staged fast-turnaround programme devised, milestones are reached every time an R&D vehicle on the next-higher scale becomes available for exploitation. Milestones are attached to each of the scales and are reached when the first deliverable on each scale is tested, analysed, and the corresponding concept validated. Corresponding deliverables at each scale are produced at the respective appropriate time intervals, as listed below. We define here milestones and deliverables on the basis of a single laboratory. Milestones and deliverables are intended to be multiplied by the number of laboratories contributing to the specific task.

- **MAG.LTSM.SMPL.Dx**: Ten to several tens of deliverables per year;
- **MAG.LTSM.SUBS.Dx**: Three to four deliverables per year;
- **MAG.LTSM.SD12.Dx**: One to two deliverables per year;
- **MAG.LTSM.LD12.Dx** and **MAG.LTSM.SD16**: One deliverable every one to two years.

The cadence of deliverables at each scale naturally slows down when the next milestone is reached. The smaller-scale R&D objects are then mostly needed to address problems encountered at a higher level, or to feed forward potential breakthrough technologies.

In addition to the above fast-turnaround multi-scale milestones and deliverables, one milestone and one deliverable are added:

- **MAG.LTSM.Mα**: At the beginning of the programme, an in-depth knowledge transfer from past and ongoing Nb_3Sn magnet R&D programmes will take place. This initial milestone will be likely organised through a series of technical meetings and laboratory visits. The transfer shall focus on what we know works well, what we know could or should be improved, and what we know we do not know. Planned for Q4 2022.
- **MAG.LTSM.Dω**: This final deliverable takes the form of a summary document, weaving all available results from the individual programmes together into one coherent and credible position, arguing whether the sum of all magnets built and tested constitutes the required demonstration of technical and financial feasibility of the FCC-hh magnet system. Planned by Q4 2026.

2.7.6 HTS magnets

2.7.6.1 Scope and objectives

As with HTS materials and cables, this R&D is of an exploratory nature. HTS magnets are the only option to generate fields beyond the reach of Nb_3Sn. Consideration of only engineering current density would suggest that magnetic fields in the range of 25 T could be generated by HTS, both with BSCCO and REBCO, as shown in Fig. 2.3. This needs to be moderated by the fact that mechanics and quench management may not be feasible, or practical, at the projected forces, stresses, stored energy and energy density. The actual limits of a feasible HTS accelerator magnet need to be established.

A second element of this R&D is triggered by the consideration that with the current cost of HTS, a full-HTS winding may not be affordable. A hybrid solution may be considered, where LTS are used in the lower magnetic field area (e.g. below 15 T), and HTS is used above. A hybrid configuration requires the use of liquid helium as coolant. At the same time, as we can clearly see in Fig. 2.3, performance of HTS in the range 10 to 20 K has reached values of J_e well in excess of 500 to 800 A/mm^2, i.e. the level that is required for compact accelerator coils. The exploration of magnet designs working in an intermediate temperature range (e.g. 10 to 20 K) and dry magnets (conduction cooled) is of considerable interest, because it would open a pathway towards a reduction of cryogenic power, a reduction of helium inventory (e.g. dry magnets), or the use of alternative cryogens, e.g. gaseous helium (GHe), or liquid hydrogen (LH2). In this case, obviously, the magnet would have to be wound completely from HTS.

For HTS, where technology is relatively immature, the work on magnet design and technology will go hand in hand with tape and cable development. As already mentioned in the R&D on HTS conductors, good uniformity of the current density over long unit lengths (from present state of the art of 200–300 m, to 1 km), and development of features matching magnet challenges (e.g. good adhesion of layers, low internal electrical resistance) or facilitating them (e.g. a ‘current flow diverter’ to increase quench propagation speed) should be prioritised above increased critical current.

The issue of HTS cables is of special importance for the magnet R&D. Cables with high current capacity are required to decrease the magnet inductance for powering and protection reasons. High-current-density options being considered are tape stacks [73,74], Roebel [76], CORC [75], and STAR [77]). The work of the coming years should determine the most suitable cables to fit the needs of accelerator magnet construction and operation. Besides the practical matter of coil winding (see below), a fundamental question to be addressed is the need for transposition. Though possibly secondary from the point of view of field quality, which is expected to be dominated by the large persistent currents contribution, the impact of transposition on performance needs to be studied. Finally, full characterisation at the scale of the cable will accompany design and analysis of demonstrator magnets. Example of high-priority activities, besides critical current, are current sharing and transfer length among tapes, basic mechanical properties, and current density dependence on angle, stress and strain. Joint technology (resistance value and joint robustness) is of utmost importance for magnet technology. Though already included in the HTS conductor R&D, this needs to be directly linked to the magnet design from the beginning of the process. Finally, the HTS conductor design may require including features necessary or beneficial to magnet protection, such as detection systems based on conductor temperature or voltage sensing and compensation.

The design of the future magnets should take into account particular characteristics of HTS tapes and cables. REBCO winding geometry tends to be constrained by the use of tapes. The end design is the main focus area, due to the tape aspect ratio making a hard-way bend difficult. Several magnet design options have emerged in the past (e.g. aligned blocks, cloverleaf and CCT) and the effort should strive to improve them, or find new ones. The coil shape should be optimised to maximise the efficient use of superconductor (e.g. reducing the field components normal to the tape), avoiding excessive margins.

Inspired by R&D on ultra-high-field solenoids, NI or PI winding configurations could be considered. This configuration, generally referred to as controlled insulation (CI), would benefit magnet protection, potentially reaching the limit of self-protection. However, we are not yet certain that CI windings are applicable to accelerator magnets, especially with regard to transient effects and stability when compared to solenoids. A design study needs to be followed by development of the necessary technology, and in particular the possibility to achieve a preset contact resistance, reproducible from coil to coil. Tests of such windings should be at reasonable parameters for accelerators (e.g. a ramp rate of 20 mT/s corresponding to 20 T in 1000 s), possibly extended to higher ramp rates relevant for other applications (e.g. 1 to 100 T/s range for ion therapy synchrotrons or the fast acceleration section of a muon collider). This question is very important since it can change dramatically the design principle not only of the magnet but also of the conductor.

HTS magnet R&D will also have to address the effects of screening currents on field quality. Magnetisation magnitude and temporal stability are one of the major drawbacks of HTS tapes and could be an issue for accelerator magnets. Control of these effects may require overshoot, vortex shaking, or temperature increase, some of which may not be compatible with accelerator operation. This has been only partially addressed in ultra-high-field solenoids, which are mainly focused on the field magnitude. While different cables and magnet designs will be explored to find the best way of achieving good field quality, we also recognise that alternative methods to control field harmonics (i.e. passive or active shimming, stronger correcting magnets) and innovative beam optics and controls may be required, to cope with features typical of HTS.

The R&D work on HTS magnets, similar to Nb_3Sn, will depend on advances in computational capability, described in detail below. Specifically, persistent currents and controlled insulation windings will require tailored developments. Several codes are already available to compute these effects, and we must pursue this effort. In the case of HTS the tape aspect ratio of 10^{-4} is a challenge when attempting to model complete cables and whole magnets. A close interaction between design, modelling, and testing will be key to foster development and understanding.

Finally, there is an obvious need for a near-future facility providing a background field for testing of HTS demonstrator magnets. FRESCA2, Supraleiter Test Anlage (SULTAN), and the planned European dipole (EDIPO) reconstruction are possible European test infrastructures, but in their present configurations they do not allow HTS dipole tests. A rapid alternative could be to realise a new FRESCA2 type magnet dedicated to this task, or join forces with other programmes to realise a background field magnet and test facility.

The structure of the program on HTS magnets is once again based on an innovation climb shown in Fig. 2.12. The first steps are exploratory and depend heavily on the result of the proposed design studies. As for Nb_3Sn, sub-scale magnet work will precede the work on the two identified routes of hybrid or all-HTS magnets. Results of this R&D will eventually join in the definition, design construction and test of HTS demonstrator magnets.

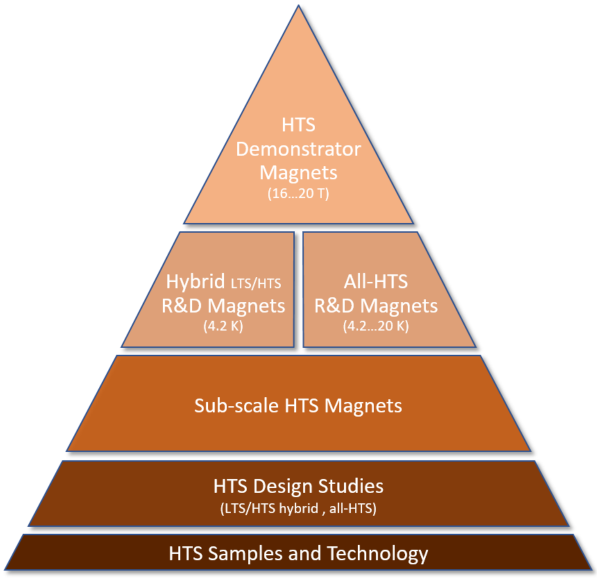

Fig. 2.12: Schematic representation of the innovation pyramid concept for HTS dipole magnets.

2.7.6.2 Identified tasks

- In synergy with the R&D on HTS conductors (tasks **MAG.HTSC.COND** and **MAG.HTSC.CABL**), and in parallel to HTS magnet design studies (task **MAG.HTSC.DSGN**), clarify and specify needs based on magnet design options and suitable technology towards the selection and qualification of cables geometry suitable for accelerators. Address at magnet level issues such as margin and mechanical effects, transposition, persistent current effects, current sharing and quench.
- **MAG.HTSC.DSGN**: Pursue a design study of HTS magnet options, including hybrid LTS/HTS for operation at liquid helium temperature (e.g. 4.2 K), or a full-HTS dipole for potential operation at higher temperature (e.g. 4.2 to 20 K). The study should include exploration of coil cross sections, end design, optimisation of tape alignment, and CI schemes.
- Participate in the development of models (tasks **MAG.MCM.MDLS** and **MAG.PETP.MDLS**), contributing test results on sub-scale and insert coils, to improve understanding and control of quench and field quality in HTS magnets, including CI winding schemes and with focus on persistent currents magnitude and stability.
- **MAG.HTSC.SUBS**: Design and manufacture sub-scale and insert coils for technology R&D, representative of the HTS magnet design being pursued, and practical for achieving a fast turnaround R&D cycle. Test the sub-scale and insert coils to validate cable (various configurations) and technology (e.g. insulation or CI, winding shape and end design, joints).
- **MAG.HTSC.SRDM**: Engineer and manufacture an HTS R&D dipole magnet as a preliminary step towards a demonstrator, with parameters to be set once a basic technology selection is reached.

2.7.6.3 Top-level milestones and deliverables

- **MAG.HTSM.M1**: Design sub-scale and insert coils for technology R&D by Q4 2023.
- **MAG.HTSM.M2**: Results of design study of hybrid LTS/HTS dipole by Q4 2024.
- **MAG.HTSM.M3**: Results of design on a full-HTS dipole by Q4 2025.

- **MAG.HTSM.M4**: Results of sub-scale and insert coil manufacturing (winding, insulation, joints, etc.) and tests performed in the period 2023–2026, completed by Q4 2026.
- **MAG.HTSM.D1**: Define a magnet specification, including field performance, of HTS accelerator dipole magnets by Q4 2026.
- **MAG.HTSM.D2**: Conceptual design of an HTS accelerator magnet by Q4 2027.
- **MAG.HTSM.M5**: Initiate the engineering, construction and first test of a HTS dipole demonstrator by Q4 2028.

2.7.7 Insulation systems, components, cryogenic and modelling technologies

2.7.7.1 Scope and objectives

Development of composite and structural magnet components. We group in this R&D activity the work on all materials and components entering in the construction of magnets, including work on samples (e.g. 10-stacks and multi-scale mock-ups) with the exclusion of superconductors, addressed elsewhere. R&D programmes are already in place in the EU and the USA on composite and structural materials and must be reinforced. A specific focus of this part of the programme is on the development and characterisation of insulation systems (polymers and reinforcement) for both Nb_3Sn and HTS magnets. The global strategy is to identify the key parameters, understand how to characterise them, measure the effect of these parameters, and possibly implement them in finite element models in the form of a shared results database. The mechanical, electrical, thermal, and tribological characterisation should be systematically undertaken from room to cryogenic temperature on different scales: single material, insulated conductor, and coil assembly integrated into a magnet. Among others, elastic modulus, stress distribution, adhesion, toughness, and thermal properties during assembly and cooling down should be investigated. Friction between the insulator and conductor components and its impact on the stress distribution within a magnet assembly should be addressed. The impact of the impregnation process and system on other parameters (such as stress distribution, internal adhesion, and interface friction) and the role of interfaces and discontinuities within the coil assembly should be explored. This programme should identify the structural and physical parameters for optimised coil assemblies under working conditions. The use of advanced imaging techniques is recommended as an aid towards understanding the nature of magnet degradation.

Thermal management of high field magnets. The cryogenic system of the next circular collider will have to cope with significantly higher thermal loads than the LHC. The choice of the FCC is to use superfluid helium at 1.9 K for cooling the cold mass of the 16 T Nb_3Sn superconducting magnets, similar to the LHC. Although superfluid helium cooling at 1.9 K is at least twice as expensive as the use of liquid helium at 4.5 K, also a possible choice for Nb_3Sn, this extra cost is largely compensated by the saving on the magnet cost and comes at the benefit of excellent heat transfer in the magnet string. A drawback is the helium inventory, which increases by a factor of six with respect to the LHC (800 tonnes of liquid helium in FCC-hh).

Using HTS magnets could be a game-changer since they can be operated at a higher temperature for at least equivalent magnetic performance. Higher temperature operation (10 to 20 K) would imply a drastic reduction of cost for the cryogenics due to a higher system efficiency, especially if novel cryogenic designs and thermal management are employed. At these temperatures, the cooling strategy will be different from the one used in the LHC, and the structure of the HTS magnets will have to contain adapted features. Thermal management of high field magnets (internal heat transfer, heat transfer to coolant, and external heat transfer to cryoplant) will require new engineering solutions, integrated from the start of the magnet design. The need for experimental validation of thermal characteristics of coil packs and the modelling of complete cold-mass designs to guide and optimise heat extraction paths under expected accelerator load are indispensable tools.

Multiscale and multi-physics modelling. A change in modelling approach is required to bridge the gap between modelling and design methodology and profit from advances in computer aided engineering (CAE). As in other fields, CAE is providing a standard for design and manufacturing, including practical cost optimisation. At the same time, mastering the challenges identified earlier will require a significant extension of modelling capabilities and a high degree of synergy between design and simulation tools.

The community has shown that the most relevant physical phenomena for HFM can be captured with multi-scale modelling and multi-model analysis. However, some of the modelling needs to be augmented, including new physics as well as multi-scale capability from the meso-scale of multi-physics analysis of a conductor to the macro-scale of a full magnet string. This applies in particular to quench initiation and propagation, a relatively new playground. Multi-model analysis and co-simulation are modern integrated design techniques, demonstrated so far at development level. We believe that the next step is to translate this progress into improved design techniques for HFM. The core idea is to focus on 'making models talk to each other' with the concept of model-based system engineering (MBSE) as a platform for collaborative modelling. This is the formalised application of modelling to support system requirements, design, analysis, verification, and validation activities, beginning in the conceptual design phase and continuing throughout development and later life cycle phases. MBSE moves from a document-centric paradigm for sharing of information to a model-based sharing of information. Models become repositories of data, queried to provide relevant information, and can be concatenated into automated workflows. We expect that adoption of this methodology will also lead to a more profound understanding of our magnets from the earliest stages of design onwards.

2.7.7.2 Identified tasks

- **MAG.MCM.MTRL**: Pursue the measurement and characterisation (constitutive equations) of the mechanical and thermo-physical properties of materials, components and composites, including new classes of materials such as metamaterials and additive fabrication materials. As a high priority activity, develop and characterise electrical insulation systems, especially relevant for wind-and-react Nb_3Sn magnets but also applicable to HTS magnets. Upgrade the facilities required for the measurement and characterisations described above, facilitate sharing, and make available the associated data repository as a reference database for magnet design.

- **MAG.MCM.THME**: Support design, construction and analysis of magnet performance in specific aspects of electro- and thermo-mechanical integrated modelling, including comprehensive analysis of manufacturing and operation conditions, aiming at preventing performance loss and degradation.

- **MAG.MCM.CRYO**: Study alternative magnet thermal designs, operating above liquid helium temperatures. Investigate operation around 10 to 20 K, towards a low helium content cold mass to reduce the inventory and the complexity of the helium management during quench, as well as a conduction-cooled thermal design with the development of high-performance thermal links. Specialise versatile conceptual thermal designs to cope with the wide variety of magnet options (Nb_3Sn and HTS) and their respective thermal loads.

- **MAG.MCM.MDLS**: Pursue the development of physics modelling of relevance to HFM (e.g. quench propagation in HTS) towards augmented modelling capability and accuracy improvement, as well as multi-scale modelling from conductor multi-physics to a magnet string. Advance co-simulation capabilities towards an ideal digital twin of an as-built magnet.

- **MAG.MCM.MBSE**: Develop and generalise the use of a Model-Based Systems Engineering (MBSE) framework as a unifying information management tool.

2.7.7.3 Top-level milestones and deliverables

- **MAG.MCM.M1**: Develop measurement facilities and characterise materials and composites relevant to HFM applications, prioritising electrical insulations for Nb_3Sn and HTS magnet. This work includes detailed material studies, advanced imaging and analytical techniques, and the development of constitutive equations. Planned by Q4 2025.
- **MAG.MCM.M2**: Develop new engineering multi-physics/multi-scale solutions for thermal management of high field magnets (Nb_3Sn and HTS), both internal (e.g. coil heat transfer to coolant) and external (e.g. heat transfer to cryoplant), including measurement of heat transfer in small samples, demonstrators and model magnets. Planned by Q4 2026.
- **MAG.MCM.M3**: Integrate and unify computational tools to support the design of conductors, demonstrators and model magnets within an MBSE framework. Specifically, integrate models adapted to the whole spectrum of multi-physics and multi-scales relevant to Nb_3Sn and HTS magnets in including the manufacturing and operation conditions. Planned by Q4 2026.

2.7.8 Magnet protection

2.7.8.1 Scope and objectives

R&D on magnet powering and protection will be devoted to the development of strategies and methods to detect and safely dump the magnet stored energy, advancing the state of the art to address the challenges outlined above. The work on LTS and HTS has both commonalities and specificities, as described below.

LTS. Quenches in Nb_3Sn magnets propagate at high velocity, and quench management at the increased stored energy density (see Fig. 2.6) is primarily a matter of decreasing detection and dump time. This evolution will require a significant improvement of instrumentation (voltage-based) and active protection devices (e.g. sturdy resistive heaters, and advanced protection techniques such as CLIQ). As the engineering margins decrease, this will also call for an improved knowledge and control of parameters like strand and cable coupling loss (critical to CLIQ).

In parallel to the above developments, it is crucial to understand the true limit of protection in impregnated Nb_3Sn coils. This work shall address failure mechanisms of thermo-mechanical origin (peak temperature, peak temperature gradient within the coil, peak temperature difference with respect to the structure) as well as electrical origin (peak voltage). This work would be best performed by measuring limits in dedicated small-scale experiments, alongside the characterisation and measurement of materials and composites described above.

Finally, as Nb_3Sn magnet technology becomes mature, quality assurance will be of primary importance, to be extended to all aspects of an accelerator magnet, such as dielectric strength and voltage withstanding, quench heater and feedthrough integration, or internal and external bus-work. Again, 'robustness' is the focus of this activity.

HTS (REBCO tapes). While the challenges of stored energy and energy density are shared with LTS, dealing with quench propagation and protection in HTS magnets requires a paradigm shift. Spontaneous quenches are unlikely, because of an enthalpy margin one to two orders of magnitude higher than in LTS, but when it happens the propagation has a speed one to two orders of magnitudes slower than in LTS. In addition, HTS can possibly operate in a temperature regime beyond liquid helium (10 to 20 K), where changes in cooling significantly affect the dynamics of the quench.

The first consequence is that voltage-based detection methods are significantly more difficult, and alternative detection methods may be needed (e.g. fibre optics, temperature sensors, acoustic sensors, hall probes, liquid helium flow measurement). A first focus of the R&D on HTS quench protection is therefore on quench detection, looking both at improved voltage-based methods, as well as alternatives to be integrated in HTS cables and magnets. The second consequence is that it is difficult to actively quench an HTS magnet. Large energies, seemingly beyond practical levels, would be needed by embedded heaters, or CLIQ, and here again alternatives are sought (e.g. secondary CLIQ). This is the second focus of R&D on quench protection in HTS magnets: determining whether active protection mechanisms are effective.

Tailored solutions used for CI solenoids are potentially of interest, but their relevance to accelerator magnets must be established, considering the electromagnetic transients during normal operation (joule dissipation and field homogeneity issues) as well as fast dump (transverse currents in between turns and associated force distribution which deviate substantially from normal design conditions). The study of CI winding will best be performed as a combination of simulation and experiments on small-scale coils that need to be designed, realised and tested.

Common considerations. Powering will require adapting the design of the cables and magnets to reduce inductance and voltages. This will need the development of concepts for magnet strings, providing design values for cable current and voltages.

Both LTS and HTS magnet design will rely on multi-physics simulation of quench, to better master evolution and margins with respect to the local limits. The development of modelling codes adapted to HTS, already mentioned in the magnet section, is essential. Special tools will need to be developed to study the protection of HTS magnets, from initiation (e.g. voltage due to current sharing) to energy dump (e.g. through CI windings). The modelling effort should span the scale from cables to magnets.

The work on powering and protection of LTS and HTS magnets should include redundancy and failure scenarios, which is of primary importance in the case of LTS/HTS hybrid designs.

Finally, the scope of the work proposed includes collection of a large amount of data from multiple diagnostic tools. The reduction and analysis of this data represent a challenge. Here we propose to resort to machine learning to look for regularities, introducing a level of artificial intelligence in the analysis of magnet tests.

2.7.8.2 Identified tasks

- **MAG.PETP.MDLS**: In close synergy with task **MAG.MCM.MDLS**, improve and develop computational models relevant to quench detection and protection in Nb_3Sn and HTS high-field magnets.
- **MAG.PETP.DSGN**: Interact closely with conductor and magnet design, providing design support to achieve suitably large detection and protection margins, compatible with string of magnets powered in series in an accelerator.
- **MAG.PETP.INST**: Explore quench detection methods for Nb_3Sn and HTS high-field magnets, from known techniques (e.g. voltage threshold and quench heaters) to alternative and novel methods and strategies (e.g. fiber optics, temperature measurements, acoustic emission). Develop and deploy quench diagnostics to assist magnet tests, identify quench origins to understand performance and qualify robust designs.
- **MAG.PETP.PROT**: Develop protection strategies, methods and devices for Nb_3Sn and HTS high-field magnets, and in particular novel technologies such as CLIQ evolutions, and passive protection of partially-insulated windings.

2.7.8.3 Top-level milestones and deliverables

- **MAG.PETP.D1**: Report the result of study and specification for magnet design parameter range (current, voltage, inductance) suitable for operation in a FCC-like magnet string, by Q4 2023.

- **MAG.PETP.M1**: Complete a survey and establish a specification of advanced diagnostics and detection techniques, by Q4 2023.
- **MAG.PETP.D2**: Report the result of study on quench in HTS, including CI windings for accelerator applications, by Q4 2023.
- **MAG.PETP.D3**: Deploy novel instrumentation to improve diagnostics, identify quench precursors and origin and quench development, by Q1 2025.
- **MAG.PETP.D4**: Report the result of study on implications of operation in a range of 10 to 20 K for detection and protection, by Q4 2025.
- **MAG.PETP.D5**: Devise a method and report the results on control and reproducibility of HTS winding properties (transverse resistance) for HTS magnet with self-protection features, by Q4 2025.
- **MAG.PETP.M2**: Complete the measurement/characterisation of thermo-mechanical and dielectric properties and establish protection-related limits, by Q4 2026.
- **MAG.PETP.D6**: Report the result of study and measurements of dump initiation in Nb_3Sn and in HTS magnets using CLIQ, its evolution, or other novel techniques, by Q4 2026.
- **MAG.PETP.M3**: Establish a measurement database on instrumented HTS cables and small coils, using voltage and alternative quench detection methods, by Q4 2026.
- **MAG.PETP.M4**: Complete the comprehensive quench detection and protection design and analysis of Nb_3Sn and HTS magnet variants, by Q4 2026.

2.7.9 Infrastructure and instruments

2.7.9.1 Scope and objectives

The programme outlined here relies critically on the availability of R&D, manufacturing, and test infrastructure, as well as on improved and novel instrumentation for measurements and diagnostics.

The concept of fast turnaround is best implemented having a distributed infrastructure, in particular workshop facilities for the construction of short magnets and demonstrators (*magnet laboratories*), as well as cryogenic test facilities for small components, samples and short magnets and demonstrators (*cryogenic test stations*). Consolidating and upgrading such distributed infrastructure, partly already available or in construction, is one of the priority activities of the initial phase of the programme.

Our analysis has further identified critical missing capabilities, ranging from facilities for the qualification of superconducting wires, tapes and cables at high magnetic field, to large size manufacturing infrastructure specifically adapted to the range of magnet designs considered. Several of these additional facilities and infrastructures may require large investments, or have large size, and would be best located at one site, to be shared by all contributors to the programme, or a wider community if applicable. This holds in particular for the infrastructure for Nb_3Sn long magnets, which is demanding in terms of space, investment and operational requirements. It is proposed to stage the procurement and construction of these facilities and infrastructures throughout the proposed phases of the programme, also engaging industry which could host some of them, as appropriate.

The significant infrastructures and facilities identified for both superconductor and magnet activities are listed below, classified as manufacturing infrastructure or test infrastructure:

Manufacturing Infrastructure.

- Rutherford-cabling machines for the development and laboratory-scale production of Nb_3Sn cables with large in-field current capability and a large number of strands (typically 40 to 60).

- Novel cabling machines for the development and production of long lengths of new types of HTS cables. This will require the prior development and demonstration of HTS cable concepts appropriate for use in accelerator magnets, which will be the outcome of the preliminary R&D phase on HTS conductor.
- Dedicated electrical insulation and braiding machines, providing the electrical insulation of cables.
- Dedicated winding machines for the production of LTS and HTS coils, operated in grey rooms and suitable for a high degree of automation.
- Short ($\sim$3 m for R&D) and long (up to $\sim$15 m for long magnets) reaction furnaces for the heat treatment of Nb_3Sn coils in controlled atmosphere.
- Short ($\sim$3 m for R&D) and long (up to $\sim$15 m for long magnets) chambers for vacuum pressure impregnation of LTS and HTS coils.
- Short and long presses and tooling for different assembly steps (e.g. curing, collaring or keying, welding).

Test infrastructure.

- Test stations for the electro-mechanical qualification of HTS and LTS wires and tapes, in external magnetic fields up to 18 T for Nb_3Sn and in excess of 20 T (ideally up to 25 T) for HTS. Liquid helium conditions are needed (1.9 K and 4.5 K) but allowing also higher temperatures (10 to 20 K range).
- A test station for HTS and LTS cables, requiring conditions of field and temperature comparable to those for single wires and tapes, but also high currents and large aperture.
- A test station consisting of a high-field magnet with a large bore, providing a background field and enabling the measurement of HTS coils in a significant magnetic field. The need of measuring HTS coils in a background magnetic field is a new input for test infrastructure, a specific requirement for the qualification of HTS sub-scale and R&D magnets.
- Vertical test stations for the test of LTS and HTS R&D and demonstrator magnets at cryogenic temperature (1.9 K and 4.5 K for Nb_3Sn, and variable temperatures from liquid helium to liquid nitrogen for HTS).
- Multi-purpose, horizontal or vertical test facilities for long cryo-magnet assemblies (including test for lengths of coils/cold masses of up to 15 m).
- Equipment for standard electrical and mechanical tests and measurements.
- Equipment for high voltage tests, tests in Paschen conditions, and partial discharge tests at small and full scales.
- Magnetic measurement benches adapted to the R&D magnets and demonstrators.

The scope of activity finally encompasses R&D on the instrumentation and diagnostics required to advance understanding of superconducting magnet science. We include here the upgrade of existing instrumentation, but also activities based on emerging techniques that can be applied and adapted to magnet R&D (e.g. diffraction, spectroscopy and imaging techniques), as well as work on novel diagnostics.

2.7.9.2 *Identified tasks*

- **MAG.IETI.INST**: R&D on novel sensors, diagnostic and instruments, in close collaboration with task **MAG.PETP.INST** for the detection and measurement of quench, and task **MAG.MCM.MTRL** for measurement technology relevant to material science.

- **MAG.IETI.PINF**: Design, specification, procurement and commissioning of conductor and magnet production facilities, including Rutherford cabling machines for Nb_3Sn, cabling machines for HTS, and infrastructure for short and long coils and magnets.
- **MAG.IETI.TCON**: Procurement or construction of test station for Nb_3Sn wire and HTS conductor at increased field, current and temperature capability.
- **MAG.IETI.TINS**: Design and engineering of cable and insert test stations for Nb_3Sn and HTS cables, and HTS sub-scale and R&D magnets.
- **MAG.IETI.TMAG**: Design, construction, commissioning and operation of vertical and horizontal test stations for R&D and demonstrator magnets, including multi-purpose and variable temperature test facilities.

2.7.9.3 Top-level milestones and deliverables

- **MAG.IETI.M1**: Complete a survey and establish a specification of advanced diagnostics and measurement techniques relevant to HFM, by Q4 2023.
- **MAG.IETI.D1**: Test station for Nb_3Sn wire commissioned, by Q4 2024.
- **MAG.IETI.D2**: Test station for HTS conductor commissioned, by Q4 2024.
- **MAG.IETI.D3**: Rutherford cabling machine for Nb_3Sn cables installed and operational, by Q1 2025.
- **MAG.IETI.D4**: Infrastructure for long Nb_3Sn coils/magnets available, by Q2 2027.
- **MAG.IETI.D5**: Multi-purpose test facility for long Nb_3Sn coils/magnets available, by Q2 2027.

2.7.10 Integrated roadmap

Figure 2.13 shows the long-term context for the overall HFM R&D programme. The timeline reported here is compatible with the integrated development plan of a Future Circular Collider, as detailed in Ref. [71].

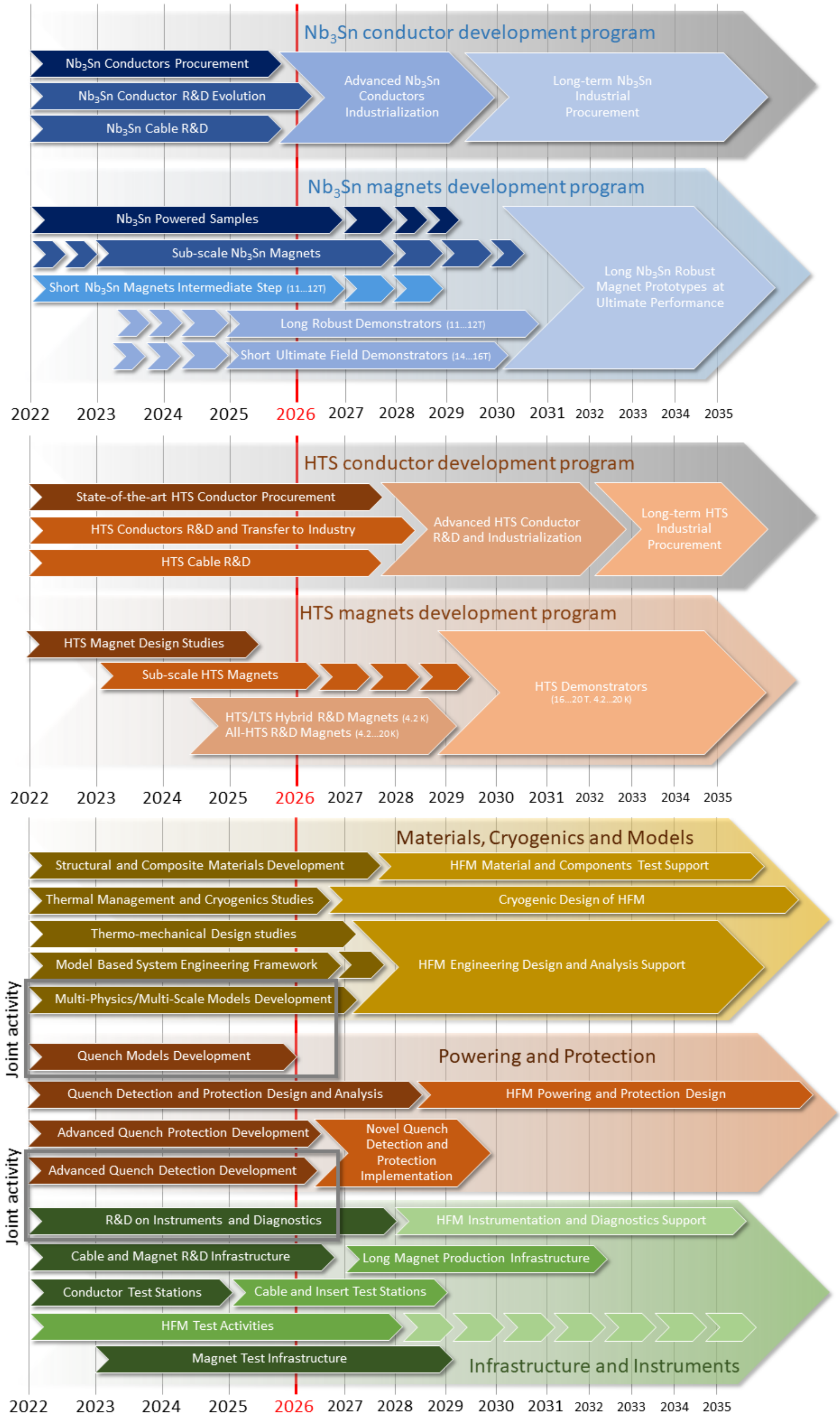

Fig. 2.13: Overview of proposed roadmap for high-field magnet development and associated technologies.

2.7.11 Resources

The cost of the programme has been estimated using a bottom-up approach. Values are quoted as material value M (in MCHF) and personnel requirement P (in FTEy for full-time equivalent-years). Personnel groups together all levels: permanent (academic and technical staff) and temporary (academic and technical staff, students, post-docs and all other forms of external support labor acting on the laboratory premises). The value was estimated taking a reference period of seven years, which is the duration that allows reaching consolidated results on both conductor and magnet technology. For comparison with other accelerator R&D areas, the cost of the first five years of the programme is also presented. The results of this evaluation are summarised in Table 2.1, where we report the total requirement for three scenarios: nominal, aspirational and minimal.

The nominal scenario corresponds to the tasks, milestones and deliverables described in the sections above. The value of this scenario is 154.4 MCHF and 607 FTEy over the seven-year reference period, or 112.9 MCHF and 478.5 FTEy over the first five years. The Nb_3Sn conductor activities require a significant investment in the procurement of superconductor, about 50% of the total material value of the activities on Nb_3Sn conductor. This procurement only marginally contributes to the conductor R&D, but is obviously necessary to *feed* the magnet development. The case is different for the HTS conductor, where tape and cable R&D dominates the cost of the programme.

The total resources in terms of material and personnel for the nominal scenario are reported in Table 2.1, providing a detailed break-down to the level of each task. The profiles in time for material and personnel are shown in Fig. 2.14 for the first five years.

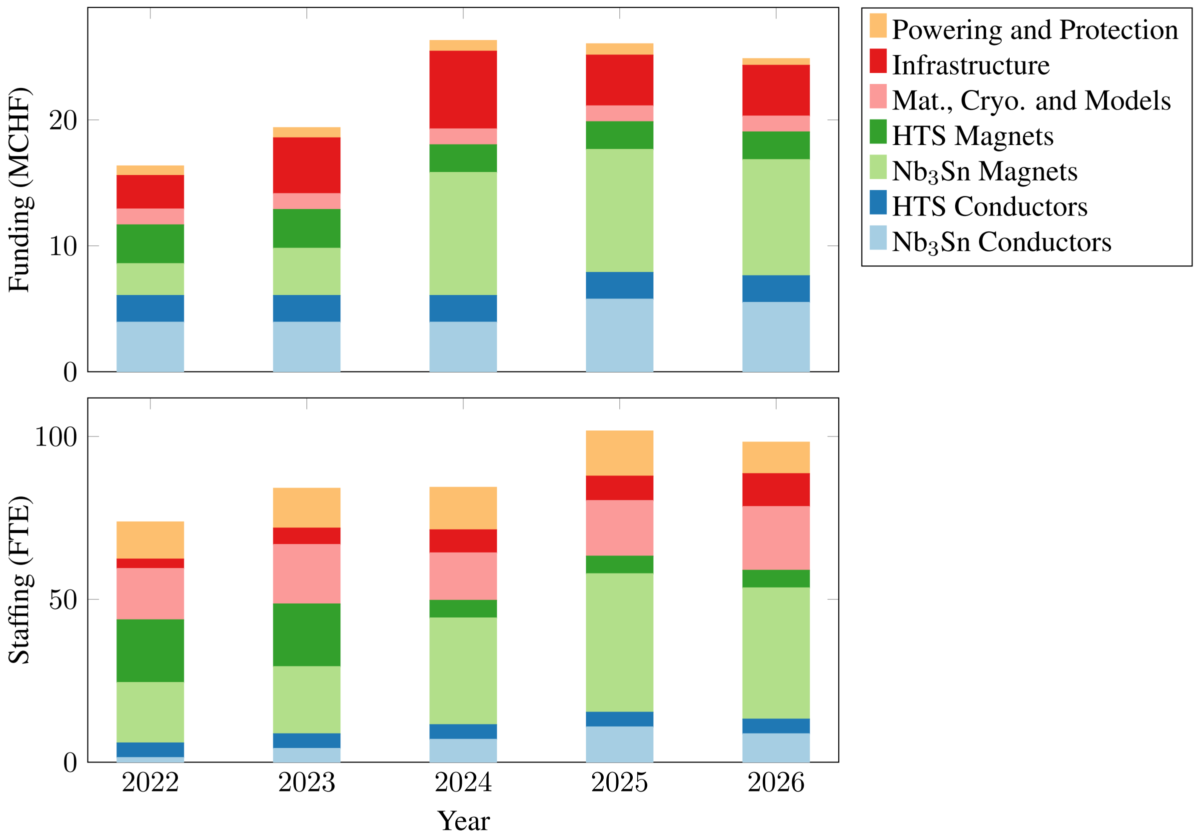

Fig. 2.14: Time profile of estimated nominal HFM material and personnel requirement for the nominal scenario.

The partial split of the total resources among the top-level tasks is shown in Fig. 2.15 over the seven-year reference period, and in Fig. 2.16 over the first five years. Material and personnel efforts are clearly focussed on Nb_3Sn conductor and magnet activities. We remark that the technology activities on Materials, Cryogenics and Models have a significant share of personnel, based on a relatively large number of students and early researchers engaged in this material science and modelling activity where innovation is expected to be at its highest.

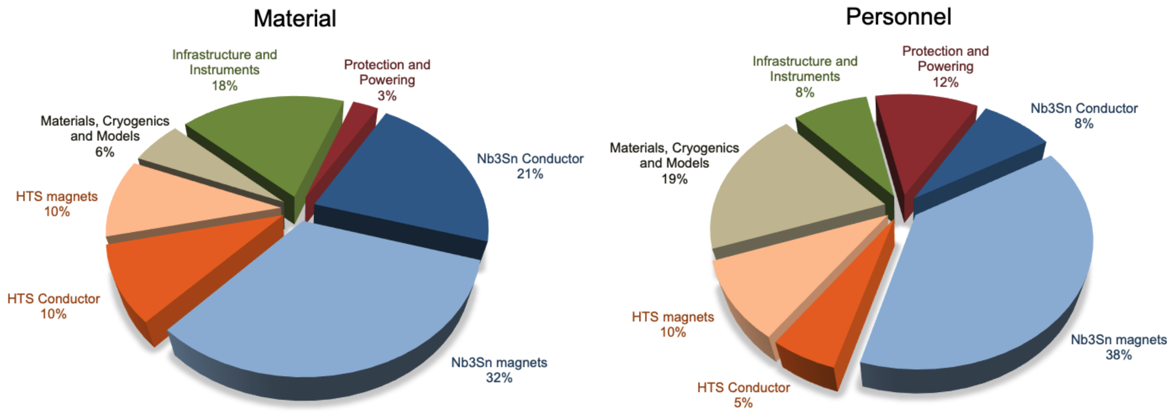

Fig. 2.15: Value of the proposed program in the nominal scenario (material and personnel) evaluated over the 7 years basis taken as reference.

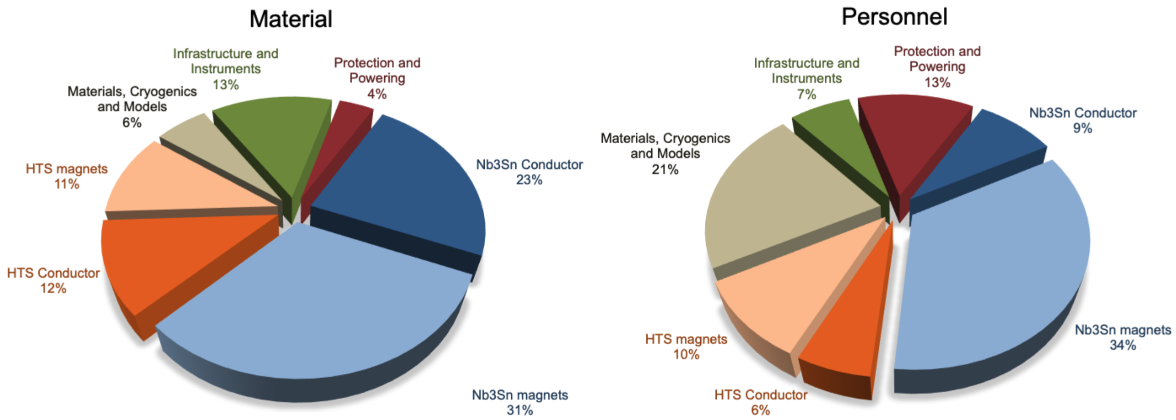

Fig. 2.16: Partial Value of the proposed program in the nominal scenario (material and personnel) evaluated after 5 years from the start.

Table 2.1: Magnet development tasks breakdown (M in MCHF and P in FTEy).

Tasks	Begin	End	Description	Nom. 5 y		Nom. 7 y		Asp. 7 y		Min. 7 y	
				M	P	M	P	M	P	M	P
MAG.LTSC.SOAP	2022	2025	Nb_3Sn conductors procurement	12.7	14.0	12.7	14.0	12.7	14.0	6.3	7.0
MAG.LTSC.COND	2022	2026	Nb_3Sn conductors R&D evolution	11.0	17.5	11.0	17.5	49.5	62.5	11.0	17.5
MAG.LTSC.CABL	2022	2025	Nb_3Sn cable R&D	2.2	10.5	2.2	10.5	2.2	10.5	2.2	10.5
MAG.LTSC.ADVP	2022	2031	Advances Nb_3Sn conductors Industrialisation	0.0	0.0	7.2	7.0	7.2	7.0	3.6	3.5
MAG.LTSC			**Total of Nb_3Sn conductor**	25.9	42.0	33.0	49.0	71.5	94.0	23.1	38.5
MAG.HTSC.SOAP	2022	2027	State-of-the-art HTS Conductor procurement	3.9	10.0	5.5	14.0	5.5	14.0	2.8	7.0
MAG.HTSC.COND	2022	2028	HTS conductors R&D and transfer to industry	5.5	7.0	5.5	7.0	5.5	7.0	0.0	0.0
MAG.HTSC.CABL	2022	2027	HTS cable R&D	3.9	10.5	3.9	10.5	3.9	10.5	1.1	5.0
MAG.HTSC			**Total of HTS conductor**	13.3	27.5	14.9	31.5	14.9	31.5	3.9	12.0
MAG.LTSM.SMPL	2022	2027	Nb_3Sn powered samples	1.6	25.0	2.2	35.0	2.2	35.0	1.1	17.0
MAG.LTSM.SUBS	2022	2028	Sub-scale Nb_3Sn magnets	7.1	35.0	9.9	49.0	9.9	49.0	5.0	25.0
MAG.LTSM.SD12	2022	2028	Short Nb_3Sn magnets intermediate step (11–12 T)	7.3	30.3	7.3	30.3	7.3	30.3	3.7	16.7
MAG.LTSM.LD12	2024	2031	Long robust demonstrators (11–12 T)	8.4	34.7	14.7	60.7	33.4	86.7	7.3	33.3
MAG.LTSM.SD16	2024	2031	Short ultimate field demonstrators (14–16 T)	11.0	40.0	15.4	56.0	15.4	56.0	7.7	28.0
MAG.LTSM			**Total of Nb_3Sn magnets**	35.4	165.0	49.5	231.0	68.2	257.0	24.8	120.0
MAG.HTSM.DSGN	2022	2025	HTS magnet design studies	4.4	32.5	4.4	32.5	4.4	32.5	2.2	16.5
MAG.HTSM.SUBS	2022	2027	Sub-scale HTS magnets	4.4	15.0	4.4	15.0	4.4	15.0	2.2	7.5
MAG.HTSM.SRDM	2024	2029	HTS/LTS hybrid (4.2 K) and all-HTS (4.2–20 K) R&D magnets	3.3	0.0	6.6	12.0	25.3	52.0	3.3	6.0
MAG.HTSM			**Total of HTS magnets**	12.1	47.5	15.4	59.5	34.1	99.5	7.7	30.0
MAG.MCM.MTRL	2022	2031	Structural and composite materials Development and characterisation	4.4	32.0	6.6	41.0	6.6	41.0	3.3	20.0
MAG.MCM.CRYO	2022	2028	Thermal management Cryogenics studies	2.2	37.0	2.2	37.0	2.2	37.0	1.1	18.0
MAG.MCM.THME	2022	2027	Thermo-mechanical design studies	0.0	11.0	0.0	12.3	0.0	12.3	0.0	6.7
MAG.MCM.MBSE	2022	2024	MBSE framework development	0.0	11.0	0.0	12.3	0.0	12.3	0.0	6.7
MAG.MCM.MDLS	2022	2027	Multi-physics and multi-scales models development	0.0	11.0	0.0	12.3	0.0	12.3	0.0	6.7
MAG.MCM			**Total of materials, cryogenics and models**	6.6	102.0	8.8	115.0	8.8	115.0	4.4	58.0
MAG.IETI.INST	2022	2028	Instrumentation diagnostics R&D	2.2	10.0	2.2	10.0	2.2	10.0	2.2	10.0
MAG.IETI.PINF	2022	2027	Cabling and magnet production R&D infrastructure	7.0	10.5	12.5	16.5	12.5	16.5	12.5	16.5
MAG.IETI.TCON	2022	2025	Conductor test stations (LTS and HTS)	3.9	6.5	3.9	6.5	3.9	6.5	3.9	6.5
MAG.IETI.TINS	2025	2029	Cables and insert test stations	0.0	1.5	5.5	4.0	5.5	4.0	5.5	4.0
MAG.IETI.TMAG	2023	2029	Magnet test infrastructure	2.2	4.0	4.4	14.0	15.4	24.0	4.4	14.0
MAG.IETI			**Total of infrastructures and instruments**	15.3	32.5	28.5	51.0	39.5	61.0	28.5	51.0
MAG.PETP.MDLS	2022	2026	Quench models development	0.0	4.0	0.0	5.0	0.0	5.0	0.0	5.0
MAG.PETP.DSGN	2022	2028	Quench detection Protection design and analysis	1.1	18.0	1.1	20.0	1.1	20.0	1.1	10.0
MAG.PETP.INST	2022	2026	Advanced quench Detection methods development	1.7	12.0	1.7	15.0	1.7	15.0	1.7	7.0
MAG.PETP.PROT	2022	2026	Advanced quench protection Strategies and methods development	1.7	28.0	1.7	30.0	1.7	30.0	1.7	15.0
MAG.PETP			**Total of powering and protection**	4.4	62.0	4.4	70.0	4.4	70.0	4.4	37.0
			Total	**112.9**	**478.5**	**154.4**	**607.0**	**241.3**	**728.0**	**96.7**	**346.5**

The aspirational scenario has been built including an upper bound of the estimated value of the following additional contributions:

- Augmented engagement with and from industry (up to 34 MCHF 2022–2027 + 100 MCHF 2027–2035).
    - Participation from the early R&D phase to the engineering review stage of methods and processes towards robust design, including considerations of cost optimisation and large-scale production (e.g. use of automation and artificial intelligence (AI)), as well as scoping tests (2025).
    - Early investment in manufacturing lines implementing a large degree of flexibility (e.g. through robotisation) and suitable at a later stage for prototyping and pre-series production of full-length magnets (of the order of 15 m) (2025–2027).
    - Once concepts are demonstrated, initiating manufacturing of long prototype magnets in preparation of a pre-series production, complementing the efforts in laboratories (2027–2035).
- Support to superconductors research and production in Europe (up to 35 MCHF 2022–2027 + 30 MCHF 2027–2035).
    - Upgrade R&D infrastructure and sustain development of technical superconductors for HFM (2027).
    - Expand collaboration with European superconductor industry in the development of advanced HFM conductors with improved electro-mechanical performance, integrating industrial perspective, and transferring novel superconductors manufacturing routes to industrial production (2027).
    - Support to superconductor production in Europe through targeted infrastructure and procurement actions (2027–2030).
- Distributed test capability at cryogenic conditions for LTS and HTS conductors and magnets (10 MCHF 2022–2027 + 15 MCHF 2027–2035).
    - Build additional test sites for liquid-helium and variable temperature testing of HFM R&D magnets (or equivalent samples) for fast turn-around in R&D mode (2025–2027).
    - Upgrade conductor and cable test capability to meet HTS target performance (20 T) (2025–2027).
    - Increase long-term cryogenic test capability in EU, test of magnet cryo-assemblies (2035).

The value of the aspirational scenario has been estimated at 241.3 MCHF and 728 FTEy over seven years. The relative split among tasks is reported in graphical form in Fig. 2.17.

Finally, a minimal scenario has been built by prioritising activities that secure conductor development and magnet research in priority areas (e.g. preventing conductor degradation and retaining magnet performance) and the construction of necessary infrastructures (in particular the test stations), while limiting magnet R&D through a focus on only a few design options. Several risks are associated with this scenario.

- While the focus is put on the development of advanced Nb_3Sn wires and REBCO, less conductor would be made available for magnet development, thus reducing the scope of manufacturing and testing.
- Reducing the number of magnet design options and reusing coils/magnet structures will increase the risks on the delivery of optimal solutions for the next ESPPU.
- Slower development of advanced technologies will thwart innovation, thus resulting in an increased risk that engineering solutions can be based only on present practice.

The value of the minimal scenario has been estimated at 96.7 MCHF and 346.5 FTEy over the reference period of seven years. Also for this scenario we have reported in graphical form the relative split among tasks, in Fig. 2.18.

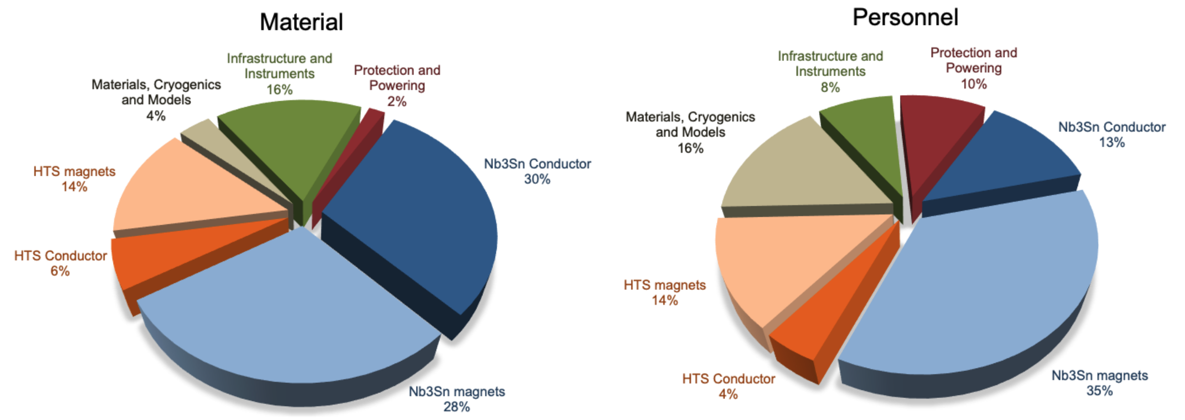

Fig. 2.17: Value of an aspirational program (material and personnel) evaluated over the 7 years basis taken as reference.

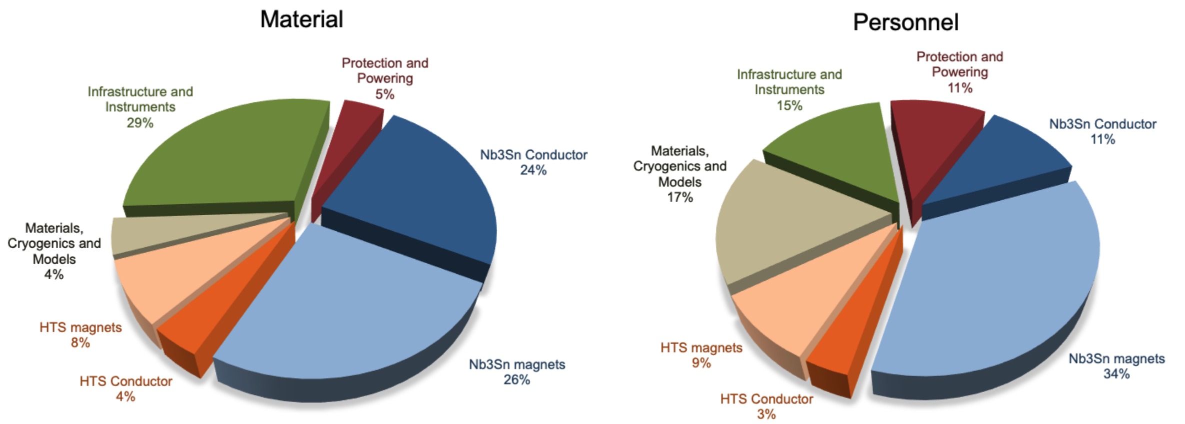

Fig. 2.18: Value of a minimal program (material and personnel) evaluated over the 7 years basis taken as reference, with increased delivery risk.

2.8 Impact of the programme

2.8.1 Applications to other fields and society

We examine here the potential of HFM for other applications in science and society, and where the availability of intense magnetic fields would enhance such applications or even bring them into being. This section is a review of the status of development of magnets for a wide range of applications and compares it to the situation of HEP accelerator magnets (HEPAM). It starts by classifying the different applications, follows with a selection of the magnet parameters that allow comparing distinct magnets, and ends with the conclusions derived from such a comparison.

Table 2.2 provides a condensed overview of the applications of high magnetic fields: how the magnetic field (B) and current (I) affect the relevant parameters for each application, how the field is produced, significant examples for every group of applications, and how high magnetic fields enhance the application.

Table 2.2: The usefulness of high magnetic fields.

Fundamentals	**Application form**	**Examples of interest**	**Why high field is required**
Laplace force per unit length ($F/l = B.I$)	Electrical machines	Energy generation; Ground, aerial & marine transportation, magnetohydrodynamics (MHD)	Increasing the force and power density > e.g. renewables; efficient ships; clean airplanes.
Magnetic pressure ($P = B^2/2\mu_0$)	Electrical machines; Magnetic bearings	Energy generation; Ground transportation	Increasing the global force and power force and density > e.g. ultra-high-speed transport.
Magnetic rigidity ($B.\rho = p/q$)	Magnets	Accelerators; Gantries; Fusion	Reducing the sizes of circular accelerators, gantries and fusion coils > e.g. ultra-high energy accelerators; ultra-compact accelerators; medical devices.
Larmor frequency ($\omega = B.\gamma$)	Magnets	NMR, MRI systems	Increasing the resolution of the system > ultra high-field NMR, MRI systems.
Magnetic energy density ($e = B^2/2\mu_0$)	Magnets	Energy storage	Increasing the specific and global energy > e.g. GJ range superconducting magnetic energy storage (SMES) for grid applications; hybrid energy storage systems.
Faraday´s law ($V = - N.d(B.S)/dt$)	Transformers; fault current limiters (FCL)	Energy transmission & distribution	Compact and environmentally friendly transformers. New FCL types > e.g. grid protection.
B itself	Magnets	Science & magnetic separation	Affects all scientific phenomena involving high fields > semiconductors, biology, etc.
I itself	Cables	Energy transmission & distribution	Increasing the current density > e.g. DC links; urban networks.

Table 2.2 includes uses where high magnetic fields are required. It also includes some where high currents are requested, since they are very much related. For the sake of efficiency, only those applications with a close link to magnets for HEPAM will be considered for comparison. The next step is to establish the most relevant parameters defining a superconducting magnet. Table 2.3 lists those parameters and the impacts and challenges associated to them. Two separate sets of magnitudes have been considered: those that can be quantified and those that are qualitative and basically associated to technological aspects.

Once these parameters have been chosen, a survey of a number of selected applications was carried out to perform a comparison between HEPAM and those for other applications. Table 2.4 summarises this survey showing ranges of values for each of the selected parameters. Two categories have been considered: state-of-the-art magnets which include those running in their present application or those which can be considered as consolidated prototypes already tested and commissioned; and future magnets, including magnets in a design phase or under fabrication and which can be presently considered the future

Table 2.3: Relevant parameters for high field magnets.

Parameter	Impact Associated challenges as field increases
QUANTITATIVE	
Magnetic field (B)	The application performance and its environment including human hazard. SC properties of the superconductor. Stress level in the magnet.
Operating temperature (T)	The cryogenic system and efficiency. SC properties of the superconductor.
Operating current Current density (J)	The power supplies, converters and current lead. SC properties of the superconductor. Stress level in the magnet.
Number of turns (N)	The operating current, energisation and stored energy. Induced voltages during quench. Winding process.
Dimensions: Bore length and volume of field (D), (L), (VoF)	Direct impact and requirements of the application and cooling. Volume of superconductor and cost, mechanical support and fabrication, quench generation, detection & protection.
Stored energy (E)	The power supplies and converters. Induced voltages and temperature during a quench. Quench protection.
Coil stress (σ)	Structural magnet design. Conductor degradation. Limitation and homogenisation of stresses.
Ramp rate (RR)	The power supply, cryogenic system, electrical insulation. Level of AC losses, wire design and manufacturing.
Maximum operating voltage (V)	The electrical insulation and thermal design. Electric field and interface superconductor to electrical insulation.
Accuracy and stability of magnetic field (FA)	The shielding and contact resistances. Development of SC switches, accurate power supplies, coils positioning.
QUALITATIVE	
SC technology	The performance, cost (operation and capital expenditures), size, etc. Conductor availability with the required quantity & specifications.
Shape of the coil	The manufacturing method. Developing adequate tooling and machinery.
Operation mode (Persistent/Driven)	The field stability. Developing superconducting switches for HTS.

direction in their respective fields.

Table 2.4 permits a number of conclusions that position HEPAM in the global context of high field magnets.

1. The meaning of high field is relative to the application. While high field user magnets aim to reach 40 T and high field NMR magnets beyond 1 GHz require 30 T, many other magnets for medical accelerators or for other applications consider 5 to 10 T as real high field that can provide significant improvements to the application. HEPAM field requirements around 20 T are in a middle range. Nevertheless, their stored energy is rather high and this constitutes an issue in terms of magnet protection.
2. HEPAM need to work at high current densities in order to make them compact. This implies working at very low temperatures with high mechanical stresses in the coils that have to be limited to avoid conductor degradation and damage. As for other applications e.g. fusion magnets, the implementation of mechanical structures limiting these stresses in the conductor constitutes one of the major challenges.
3. While in HEPAM weight is not an issue, in some other applications it can be crucial. In this regard, there is a clear tendency to eliminate the iron closing the magnetic flux path using additional

Table 2.4: Values of the relevant parameters for present and future high-field magnets for different applications.

APPLICATIONS	STATUS	MAGNET TYPE	Magnetic field (T)	Temperature (K)	Current density (A/mm^2)	Bore (mm)	Coil stress (MPa)	Stored energy (MJ)	PROPOSED MAGNET TECHNOLOGY
HEP MAGNETS	pre	q-Pole	11	1.9	500	60	115	15	Race-track $\cos\theta$ + cold iron Nb_3Sn
	fut	q-Pole	16	1.9		60	130	35	Flat race-track + cold iron. Nb_3Sn (among other several configurations)
FUSION	pre	Toroid	12	4.5	~ 600	14.700		2.200	ITER radial plates for toroidal field coils
	fut	Toroid	20	4.5–20		3000–4000			Compact HTS partially insulated coils
THERAPY ACCELERATORS	pre	Solenoid	< 8.9	4.5		700		9.6	Solenoid Nb_3Sn + warm iron
	fut	Solenoid	< 8.9	4.5		700		32	Solenoid Nb_3Sn. No iron
OTHER MEDICAL ACCELERATORS	pre	Solenoid	< 4.5	< 5.5	< 100	< 400		< 0.3	Solenoid Nb-Ti + warm or cold iron
	fut	Solenoid	< 4.5		<130				Solenoid Nb-Ti + warm iron + cold holmium poles
	fut	Solenoid	2.6	30					REBCO tapes. No iron
GANTRIES	pre	q-Pole	2.9	4.2		30			Race-track $\cos\theta$ + cold iron. Nb-Ti. Conduction cooled Surface Nb-Ti coils
	fut	q-Pole	6	4.2		30			Race-track $\cos\theta$ REBCO. Cold iron. Conduction cooled
	fut	q-Pole	4	4.2		46			CCT coils. Nb-Ti. Conduction Cooled
	fut	Toroid	3.5	4.2	105	800	50	30	Pancakes in a toroidal arrangement. Nb-Ti
	fut	Toroid	3.5	4.2	90	800	50	30	Pancakes in a toroidal arrangement. REBCO tapes
NMR	pre	Solenoid	< 28	2		540			Solenoid LTS + BiSCO persistent
	fut	Solenoid	30.5						Solenoid LTS + ReBCO non insulated
	fut	Solenoid	18.7	10–20					Solenoid HTS helium free
MRI	pre	Solenoid	11.7	1.8	25–39	900	150	338	Nb-Ti. Double pancake. No iron
	fut	Solenoid	14.1	4.2	50–70	600–700		180	Nb-Ti + Nb_3Sn. No iron
	fut	Solenoid	2.9	7	120	560		1.6	HTS pancake coils
HIGH-FIELD FACILITIES	pre	Solenoid	32	4.2	200	34 clear bore	360	8.3	Solenoid LTS + HTS double pancake
	fut	Solenoid	40	4.2	> 600	34			Solenoid LTS + HTS double pancake

superconducting coils. In other cases, it has been proposed to used magnetic materials with higher saturation fields.

4. While for some applications increasing the field is a real and challenging requirement (HEPAM is a good example) in many others it is preferred to increase the operational temperature in order to decrease the cost of operation, to reduce the complexity of the facility, or to extend its use.

5. Regarding the type of superconductor to be used, there are basically two categories: those applications for which magnetic fields lower than 5 T are enough (some medical applications, most of magnetic resonance imaging (MRI), most of gantries) and those which need fields beyond 10 T (HEPAM, NMR, some MRI).

6. For the first group there are two choices: using the conventional technology based on Nb-Ti working below 5 K or using HTS to work at temperatures up to 30 K allowing a significant reduction of operational cost and complexity for the cryogenic facility. This second group is under development and constitutes one of the trends in magnet technology.

7. For the second group, practically all the applications consider a graded configuration of the mag-

nets with sections made from Nb-Ti, Nb_3Sn and eventually HTS. This scheme requires working at low temperature but reduces the amount of needed HTS. Future proposal consider eliminating Nb-Ti and even Nb_3Sn, allowing to increase the working temperature to reduce operation costs, but this seems to be a long-term development that will not be available before the next decade. Future HEPAM belong to the second group. They will include a Nb_3Sn section and probably an inner HTS section.

8. A particular case of these graded magnets are hybrid magnets in which one of the sections is resistive. Their field of application seems to be restricted to high-field laboratory magnets due to the power consumption that they require.

9. Regarding the different magnet topologies, there are a number of possibilities which are common to all the applications: a) race-track coils (flat or curved); b) solenoids; c) canted cosinus theta (CCT) and d) flat double pancakes to configure different arrangements like solenoids or toroids. HEPAM coil configurations are not yet fixed and at present many are under development. Besides those mentioned in the previous point, others like the common coil or the block coil are under consideration for the next generation of magnets.

2.8.2 Industrial ecosystem

The section examines the impact of the HFM roadmap on industry, and is based on interviews with senior experts from the LTS, HTS and magnet manufacturing industry, representing leading European companies in this field (Bruker, Theva, Bilfinger Noell). The experts were asked to recommend specific actions from the industry point of view and their feedback was summarised and condensed to the main points.

The main industrial challenges for developing HFM for accelerators are:

- The availability of suitable conductor at low cost and high quality, since the conductor is the major cost driver. High quality relies on a reliable and reproducible manufacturing process with a high yield for long lengths and high throughput. To develop a suitable conductor the requirements need to be defined at a very early stage together with industry. This is strongly recommended, to better understand the implications and dependencies between requirements and manufacturing efforts.
- A qualified group of all partners must be brought together because multidisciplinary cutting-edge technology needs to be developed first and then exploited for efficient series production. Experts, gathered in a network of excellence, are needed for all development processes across different stakeholders, and it is recommended to exchange them also directly with industry.

It is mandatory for industry to make profit from their products and services. In general, growth and the opportunity for profit increases the interest of industry and triggers innovation and investment by companies. This has been proven by the huge progress in LTS material development within the ITER and LHC projects. Therefore, a continuous, long lasting and serious R&D programme in accelerator magnets would certainly improve the material towards higher quality, resulting in higher throughput, higher performance and lower cost of the material. This will help to transform the material into a conductor that is applicable to high-field magnets for future accelerators.

Special material aspects and measures. Superconducting materials for high-field accelerator magnets have special and unique requirements that are not often needed in other superconducting applications. Therefore, a dedicated R&D process is needed to develop the conductor and the respective manufacturing processes. After this is done, the LTS and HTS material industry is prepared to increase the capacity but needs a reliable purchase plan for this in order to make profit. Setting up new manufacturing routes or factories requires a major investment (exceeding 10 MCHF) and this cannot be done without a purchase plan. Nevertheless, we assume at present that the main drivers for market increase of HTS conductors will likely come from other application fields. To convince investors to set up a new manufacturing route, it is necessary to have reliable framework agreements and both R&D and delivery contracts. The material cost is split roughly into four parts: material cost, machine use, labour use and yield. This means that increasing yield and throughput are the main factors in decreasing material cost.

Special magnet aspects and measures. HFM for accelerators are complex and unique, and require expertise from many disciplines and fields. Therefore, an early engagement of industry is mandatory to find a balance between high requirements and their effects on development and series production. Usually this very special development does not lead to a new product line for the industry with huge follow-on prospects, but it helps to keep and further develop the expertise in the industry throughout the many manufacturing, production and testing steps. The main benefits of an HFM roadmap on industry are that: a few technology aspects can be used in other fields; the working capacity of key persons is better utilised; the know-how in specific fields can be expanded; and industry is better prepared for follow-on projects. As an example, a detailed roadmap with clear and increasing involvement of industry could try to avoid long time gaps between first demonstrators and final production as seen in previous accelerator projects. In these gaps of several years it was difficult for industry to keep the experts and know-how in the company, leading to delays.

Special cooperation aspects and measures. Maintenance and development of expertise at all stakeholders is mandatory, and long-term partnerships between laboratories, academia and industry are an optimal way to achieve this. To keep industry expertise at a high level during the long path through R&D, prototyping, and pre-industrialisation to series production, it is mandatory to establish a strong and enduring collaboration. The engagement of industry usually increases from R&D towards series production. A long-term accelerator strategy and roadmap, including a progressive programme of demonstrators and prototypes, will provide a predictable workload for industry and will help to keep and extend industrial know-how in this field. Since know-how in industry will be extended, especially while going towards high-field high-temperature superconducting magnets, such a development will help to improve the product portfolio. There is a need to explore new (for Europe) means of collaboration between laboratories and industry.

2.8.3 Training and education

The HFM programme constitutes an integrated multidisciplinary environment which may be used as a platform for developing knowledge and sharing experiences, best practices and benchmarks of the HFM technological development cycle. This will further develop links between universities, research centers and industrial partners across several countries. Training a new generation of researchers and professionals across the whole development cycle of HFM research and engineering must be an integral part of the programme mission. The material sciences, electrical engineering, cryogenics, mechanical engineering, and applied and fundamental superconductivity and magnetism communities will be connected into a single cross-sectorial R&D, opening unique interdisciplinary opportunities for fostering a solid European network for superconductivity applications that will last beyond the HFM programme itself.

The programme builds upon other EU initiatives such as EuroCirCol [78], ARIES [79] , EASITrain [80], and can be promoted through tailored initiatives at existing applied superconductivity, materials and cryogenics conferences and schools. The goal will be to promote the exchange of members, fulfill needs, foster the development in the area of accelerator science and technology, and in particular applied superconductivity and attract early career researchers to join the HFM effort. To achieve these objectives, the following specific actions should be undertaken:

- Encourage researchers and engineers to present and disseminate their activities at the school level to attract youngsters in this domain of science and technology and especially applied superconductivity;

- Provide introductory courses to the concepts of accelerator science, engineering and technology aimed at undergraduate students to increase the attractiveness of our field through new or existing events such as the CERN Accelerator School (CAS) or the Joint Universities Accelerator School (JUAS);
- Create or join a cross-sector network structure for early-researchers or PhD students (e.g. Marie Skłodowska-Curie Actions[3]) to develop the talents of the next generation of researchers and engineers, involving both academic laboratories and small and medium-sized enterprises;
- Coordinate, organise and support advanced topical training activities for technicians, engineers, graduate students and early-stage researchers in Europe, in a worldwide context, on the HFM technologies and related fields through dedicated programmes of personnel exchange among laboratories, in the frame of existing or new initiatives (e.g. COST actions[4]);
- Create an open, inclusive, gender-balanced network of excellence to promote synergies among partners by harboring an exchange programme at different levels (technicians and scientists) through which fundamental knowledge, experimental skills and engineering techniques are mutualised in the area of high-field magnet science and technology as well as related fields;
- Coordinate, support and strengthen the communications and outreach activities for accelerators in Europe focusing on the technical and social implication of the HFM programme, using a variety of communication channels.

2.9 Conclusion

High-field superconducting accelerator magnets are a key enabling technology for HEP accelerators. It was so in the past and so it will be in the future, strengthening the fruitful collaboration of the past 50 years. The present state of the art in HFM is based on Nb_3Sn, with magnets producing fields in the range of 11 to 14 T. We have tackled in the last years the challenges associated with the brittle nature of this material, but we realise that more work is required and that manufacturing is not robust enough to be considered ready at an industrial scale.

Great interest has been stirred in recent years by the progress achieved on HTS, not only in the fabrication of demonstrators for particle physics, but also in the successful test of magnets in other fields of application such as fusion and power generation. This shows that the performance of HTS magnets will exceed that of the Nb_3Sn, and also that the two technologies can be complementary to produce fields in the range of 20 T, and possibly higher.

The HFM programme described here should enable us to propose, by the next update of the European strategy, a Nb_3Sn magnet technology and a field level that can be used for a future particle collider, and to determine the prospects for the use of magnets using HTS superconductors. The main goal of the programme is to find the optimal intersection between affordability, robustness and performance.

To achieve this, the HFM programme proposes a strategy based on three main development axes, focusing on: Nb_3Sn and HTS conductors; Nb_3Sn magnets; and HTS magnets. Cross-cutting support activities include: materials, cryogenics and modelling; powering and protection; and infrastructures and instruments. The methodology of the proposed programme is based on sequential development happening in steps of increasing complexity and integration, from samples, to small scale magnets, short magnets and long magnets in order to produce a fast-moving technology progression. We are convinced that fast-tracking and innovation are crucial to meeting the declared goals on a reasonable time scale.

[3] https://marie-sklodowska-curie-actions.ec.europa.eu/about-marie-sklodowska-curie-actions
[4] https://www.cost.eu/cost-actions/what-are-cost-actions/

For Nb_3Sn conductor, the tasks identified are the development of new robust wires for industrial production, and optimisation of the necessary cables. A similar approach is proposed for HTS, although here work is more at R&D level, and industrialisation is less imminent than for Nb_3Sn.

For Nb_3Sn magnets, two objectives have been defined: the development of a 12 T demonstrator of proven robustness suitable for industrialisation, in parallel to the development of an accelerator demonstrator dipole reaching the ultimate field for this material, towards the target of 16 T.

For HTS magnets, a dual objective is proposed: the development of a hybrid LTS/HTS accelerator magnet demonstrator and a full HTS accelerator magnet demonstrator, with a target of 20 T and the potential for operation at temperatures higher than liquid helium, albeit at reduced field.

Nb_3Sn is today the natural reference for future accelerator magnets, but HTS represents a real opportunity provided the current trend of production and price reduction is sustainable. Energy efficiency efforts in line with societal trends should also be retained as one of the objectives when developing the next generation of magnets. The use of HTS conductors operated at higher temperatures could be a step in the right direction.

We recognise and highlight the crucial role of infrastructure for the manufacturing and measurement of magnets. This is an essential part of the programme, and the required facilities, equipment and instrumentation have also been identified. The funding identified will allow leaving a significant inheritance of infrastructure for future programmes. We have also discussed to some extent the impact of the development of HFM magnets on the industrial ecosystem and on the training and education of future generations of applied scientists. One of the objectives of our aspirational scenario is to propose actions to support European industry, responding to the ongoing evolution of business models and fostering the deployment of developments and innovations from research to industry.

Finally, we would like to emphasise the values of collaboration, and the connection to the ongoing programmes worldwide. Realising the proposed HFM programme will build a broad and resilient basis of competence, a strong community, and the opportunity to educate the future generation on subjects of high-technological content.

The challenge for the next decade is considerable, but the high-field magnet community is ready to meet it.

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