Proposal template Part B: technical description

EuMAHTS

Magnet technology Advances for European research infrastructures through HTS

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List of participants

Participant No. *	**Participant organisation name**	**Country**
1 (Coordinator)	CERN	
	CEA	
	CIEMAT	
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	EMFL	
	ESRF	
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	INFN	
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	PSI	
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1. Excellence #@REL-EVA-RE@#

1.1 Objectives and ambition #@PRJ-OBJ-PO@#

The prime objective of EuMAHTS (Magnet technology Advances for European research infrastructures trough HTS) is to advance High Temperature Superconductor (HTS) magnet technology and demonstrate the perceived disruptive potential of this class of superconductors for Research Infrastructures, with transdisciplinary scope and with implications on societal application. We target in particular Research Infrastructures of High Energy Physics, Light Sources and Free Electron Lasers, Nuclear Physics, Materials and Life Sciences, with non-scientific translational applications on Medical and Energy fields.

We wish with EuMAHTS not only to demonstrate higher magnetic field reach, but also to develop technology for energy efficient, compact, cost effective, and sustainable devices, as will be crucial to maintaining long term capability and leadership of European Research Infrastructure.

This ambitious objective will be achieved by designing, building and testing three prototype magnets that implement a high degree of technology innovation, as made possible only by resorting on the unique performance and characteristics of HTS. The prototype magnets not only represent grand technology challenges, they will also act as catalysts for the efforts of the Participants to EuMAHTS.

We will thus bridge the gap between laboratory realizations and deployment, aiming at increased Technology Readiness Level (TRL) by two units, from present level of TRL 3–4 (laboratory demonstration) to a level of TRL 5–6 (demonstration in industrial relevant environment). We have taken this projected increase of TRL as the main measurable and verifiable indicator of success of EuMAHTS.

The objectives of EuMAHTS require a strong connection with European industry, who will take active part in two formats: via co-development of prototypes and, in a more advanced collaborative approach, through a dedicated co-innovation program included in the scope of EuMAHTS.

The prototype magnets proposed are not only conceptual technology challenges, they are directly inspired and represent the next step in magnet technology for scientific Research Infrastructures and will have immediate implications in societal application. The direct involvement of industry in EuMAHTS will hence prepare European industry response to upcoming requests for such technology, as well as facilitate market penetration of HTS magnet technology in a near future.

EuMAHTS is the culmination of 15 years of European research devoted to studying, developing concepts and proofs of principle of magnet technology. It is participated by the most relevant research institutions and universities involved on accelerator technologies and its applications. Initiated with FP7-EuCARD (2009-2013), the research has proceeded as part of the successful studies FP7-EuroTapes (2012-2017), FP7-EuCARD2 (2013-2017), H2020-ARIES (2017-2022), and the present H2020-I.FAST(2021-2025). EuMAHTS is the hinge, where we bring to fruition the investments of long and successful research lines towards enhanced scientific competitiveness of European Research Infrastructures, this time in a transdisciplinary view and with a more ambitious program of collaboration with industry.

1.1.1 Background

Nearly forty years after their discovery [1986-BED], High-Temperature Superconductors (HTS) are on the verge of becoming game changers in magnet technology. This is the result of a combination of factors, including advances in material performance, the success of laboratory and industry projects based on the use of HTS [2020-BRU, 2016-WEI] and the development of high field magnets for compact fusion reactors that could accelerate the energy transition [2021-MIT]. This has driven large investment at manufacturing sites resulting in significant cost reduction [2021-MOL]. And, most important, the heightened awareness on the importance of energy efficiency and sustainability is a strong motivator for magnets operating at temperature higher than liquid helium, as well as reducing the inventory of cryogenic fluids.

The commonplace definition of HTS materials is to exhibit superconducting properties at higher temperatures when compared to Low Temperature Superconductors (LTS). This avoids some of the engineering complexity of cryogenics, and has spurred initial interest for various electrical engineering applications. In reality, however, it is the sum of several properties that is driving a keen interest for this new magnet technology, namely:

- Because of their large critical field, HTS materials can sustain exceptionally strong magnetic fields, surpassing by far the capabilities of LTS materials. As shown in Fig. 1, the engineering current density J_E of industrial REBCO and BSCCO-2212 at liquid helium temperature is 1000 A/mm^2, and higher, in the range of field 20T to 40T, thus opening the path to new applications in research, materials and life sciences, energy generation and transportation. These applications would not be possible without HTS;

Fig. 1 Engineering current density J_E as a function of magnetic field and temperature for technical high-field superconductors (REBCO, BSCCO-2212, Nb_3Sn) available on the market.

- Profiting from the high values of engineering current density quoted above, HTS materials also allow for the design of smaller and lighter magnet systems compared to LTS materials. Compactness, in turn, can yield lower system cost for the same performance, or higher performance for the same cost. This is a natural trend in magnets towards higher fields, as shown schematically in Fig. 2 for the superconducting Nb-Ti and Nb_3Sn accelerator dipoles of the last forty years. The engineering current density has increased, reaching approximately 650 A/mm^2 in the Nb_3Sn magnets for the High-Luminosity LHC. It is expected that the next generation of magnets, e.g. 20 T dipoles, will require further increase to remain affordable. In fact, the performance limits of magnets with such high current density come from mechanics and quench protection, for which we will devise and implement novel solutions, as described later;

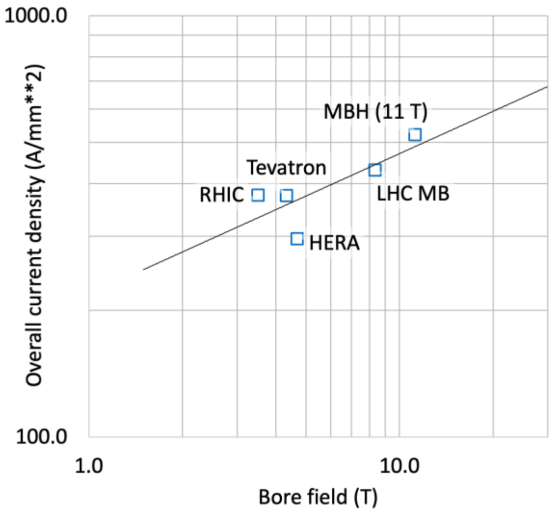

Fig. 2 Je vs. B of accelerator dipole magnets in Nb-Ti and Nb_3Sn

- Finally, HTS magnets can be operated at temperature higher than LTS magnets of similar, or lower performance. As also shown in Fig. 1, in the range of 20 K and 20 T, HTS materials still have considerable engineering current density, sufficient to build compact magnetic systems. When properly optimized, a cryogenic cycle with higher temperature at the cold end also has a higher Coefficient of Performance (COP). Hence, HTS systems tailored for operation at temperature higher than liquid helium offer higher energy efficiency and lower power consumption than equivalent LTS systems. An additional benefit is that from the range of 20 K upwards it will be possible to reduce helium inventory, or devising systems running on a different cryogen, thus reducing the risk associated with helium supply.

All in all, these considerations show that HTS magnets can lead to high-performance, environmentally friendly systems, improve sustainability, and achieve profitable economics over the long term.

Research Infrastructures in several fields in the scientific domain could profit from the above properties of HTS materials, having a direct implication on specific societal applications. To cite only the most prominent:

- Fundamental Research: HTS magnets can significantly enhance scientific capability by enabling more powerful and compact devices, such as particle accelerators for high-energy and nuclear physics [2022-LDG], light sources with improved analysis power [2018-LEA], high magnetic field user facility to study the characteristics of materials under extreme conditions [2005-NAS, 2013-NAS] and for the analysis of the structure of matter [2014-STO];

- Healthcare and Life Sciences: HTS magnets are expected to further enhance analysis devices like NMR (Nuclear Magnetic Resonance) [2018-QUI] and medical imaging devices like MRI (Magnetic Resonance Imaging) [2017-MOS], increasing resolving power, enabling higher resolution images, potentially reducing the time patients spend in a scanner, and making such machines more widely spread because of simplified cryogenics. Compact and high field HTS accelerator magnets will benefit accelerators and gantries for particle therapy, decreasing their size, electrical consumption and thus facilitating their diffusion.

- Energy Generation and storage: HTS materials may improve the performance and efficiency of electrical generation and conversion systems, as well as serving to the efficient integration of storage systems. This includes applications in magnetically confined fusion reactors, where HTS magnets could play a critical role in creating the magnetic fields necessary for plasma confinement in compact reactors, or simplified engineering profiting from operation at higher temperature than liquid helium.

- Transportation: HTS magnets could revolutionize transportation, especially with the development of compact airborne motors for all-electric aircrafts with minimal carbon footprint, and maglev (magnetic levitation) trains that can operate at higher speed and lower energy consumption.

EuMAHTS focusses on HTS magnets, and includes considerations relevant for all the above fields of application, attempting for the first time to develop an integrated strategic roadmap for the future development of HTS magnet technology, leveraging on the efforts in each field, and producing results that will induce critical progress for the research infrastructures related with accelerators, light sources and analytics instrumentation. This progress will enlarge the scientific scope of these infrastructures as well expand their communities of users towards new level of frontier science. In this sense, EuMAHTS will contribute to the world leadership of our flagship infrastructures on critical scientific sectors.

1.1.2 State of the art

The progress of HTS magnet technology in the past years has been remarkable. We have selected below specific achievements that give a good impression of the present state of the art, and provide the basis for the identification of the main directions of development of the coming years.

Materials and Life Sciences in high magnetic field

It is fair to say that it was the push towards high magnetic fields for materials and life science that triggered a revolution of HTS magnet technology in the turn of 2000. Initial demonstration experiments were typically conducted at laboratories by powering small demonstration coils (insert) in the bore of a resistive background magnet. Both REBCO and BSCCO-2212 were tested at the National High Magnetic Field Laboratory (NHMFL) in Tallahassee, FL, while activities at the Laboratoire Nationale de Champs Magnetiques Intenses (LNCMI) in Grenoble, FR, focussed on REBCO coils.

The above demonstration tests continued the progression towards higher fields [2019-NAT] were instrumental to securing the technology path that led to the successful design and construction of the all-superconducting 32 T user facility at NHMFL, a nested solenoid with a HTS insert installed in a LTS outsert [2016-WEI]. The 32 T has been running as a user facility with diverse fortune since 2014. While highly successful in blazing the path of this new technology for a direct application, it has also demonstrated that mechanics, and especially the presence of considerable internal forces originating from shielding currents in a tape that has delicate properties, can lead to performance limitations and degradation that were not identified in the original program.

Further research on small size insert coils has recently moved to the use of “non-insulated” (NI) windings[1].

[1] NI windings [2018-HAH] are referred to with different names, e.g. Metal Insulated (MI), Controlled Insulation (CI), Resistive Insulated (RI). In all cases they refer to the absence of a dielectric among turns, where the turns are effectively in electrical contact with different range of resistance depending on the presence or absence of resistive barriers.

Initiated at MIT, this is in fact based on an idea dating back to the 1960's that superconducting coils may not need insulation among turns [1962-BER]. The NI technique produces extremely compact windings, i.e. achieving the high current density targets indicated earlier, and benefits from very fast normal zone propagation in case of a resistive transition, highly beneficial for quench protection. This has led to the record production of fields up to 45.5 T at NHMFL in 2019 (14.4 T produced by an HTS coil in a background 31.1 T resistive field) [2019-HAH] and 32.5 T at LNCMI also in 2019 (14.5 T produced by an HTS coil in a background 18 T resistive field) [2016-WEI].

NI technology was at the basis of the successful design and construction of the all-HTS 26 T 35 mm solenoid installed at the Center for Axion and Precision Physics Research (CAPP) as a user facility magnet for the Institute for Basic Science (IBS) in Korea. INFORMATION ON PERFORMANCE AND DEGRADATION ?

In parallel, NHMFL is pursuing research on BSCCO-2212 inserts and has recently demonstrated production of fields of 34 T, of which 3 T were produced by a small HTS insert coil running at 450 A/mm^2 engineering current density, placed in a 31 T background field. Compared to REBCO, BSCCO-2212 comes in round and multi-filamentary form, but requires a high temperature heat treatment and is much more sensitive to stress and strain. The above test has shown that it is possible to contain and limit the electromagnetic load by internal reinforcement [2019-BOS]

Work is in progress to consolidate these achievements, and push forward. Among the various initiative, the most advanced are the 40 T project at the NHMFL, presently in the final validation phase before beginning of construction [2020-BAI], and the 40 T projects at CNRS-LNCMI and CEA, with contributions from national funding [2021-FAS] and subject of the EU design study SuperEMFL [2021-SUP]. Both researches will rely on the use of REBCO for the HTS part.

Given the apparent similarity to the objectives of EuMAHTS, we underline already here that the above projects, and in particular SuperEMFL, are directed towards an outsert/insert solution, while EuMAHTS wishes to advance by one more step towards an all-HTS magnet technology with the benefit of compactness and the possibility to operate at temperature higher than liquid helium.

The field of NMR has greatly profited from the developments described earlier, and HTS has already made a difference in research capability, in systems built in laboratory as well as industry. Developments at Riken have reached a proton resonance frequency of 1.02 GHz, corresponding to a field of 24 T, using a hybrid magnet with LTS outsert and BSCCO-2223 insert [2022-YAN]. The commercial line of NMR machines produced by Bruker Biospin are the most successful industrial realization of the potential of HTS. The high-end systems perform analysis up to a proton resonance frequency of 1.2 GHz, corresponding to a field on the sample of 28.2 T over a clear bore of 54 mm. This is achieved in a hybrid magnet, with LTS outsert and REBCO insert [Wikus]. Besides the field reach, what is also of extreme importance to the quality of the NMR data is the field homogeneity and the persistence, for which suitable solutions were found. These are spectacular achievements, also considering the fact that thanks to the use of HTS the dimensions of a GHz-class system could be reduced from the 4 m height and 2.3 m diameter of the first systems operating at superfluid helium (Ascend 1.0 GHz) to the present value of 2.8 m height and 1.5 m diameter of the equivalent systems operating at liquid helium (4.2 K, Ascend Evo 1.0GHz) [2022-BRU]

Similar to the case of magnets for basic research, the future of NMR is expected to progress further in the coming years towards the range of 30 T to 35 T (1.3 GHz to 1.5 GHz proton resonance frequency). Also in this case the material of choice for the high field part of the magnets is REBCO.

The scope of EuMAHTS, and specifically the ultra-high-field prototype (WP6), is directly relevant and applicable to progress in high field magnets for materials and life sciences.

Fusion magnets

Superconducting magnets are one of the crucial technologies for nuclear fusion. This holds true since the beginning, and most relevant in. a long line of large-scale tokamak and stellarator experiments: T-7, T-15, Tore-Supra, K-STAR, SST, EAST and W7X. Among the various fusion devices employing this technology, JT-60SA is presently the largest operational superconducting tokamak in the world. Furthermore, numerous worldwide projects are in various stages of design and construction. Among these, the ITER project is the most significant currently under construction, but we also quote DTT, and BEST, a step towards CFETR in China. All above realizations and projects rely on LTS magnet technology. There is however a growing interest in the use of HTS for fusion reactors.

The SPARC project is one such examples. In the mind of the proponents, the use of HTS for tokamak magnets offers the potential for more efficient, powerful, and compact reactors. Indeed, high magnetic fields directly contribute to reach the conditions to sustain a net positive energy output from the fusion process given that the triple product scales with the 3rd power of the on-axis magnetic field and that the fusion power scales with the 4th power (typically called the B3–B4 dependence for fusion performance) [2016-WHI]. This explains why initial interest in HTS for fusion magnets was sparked by their potential to generate higher magnetic fields compared to conventional low-temperature superconductors, thus yielding more compact machines. In addition, operating at higher temperatures than conventional superconductors would reduce the complexity, and cost, of the whole system [2023-FED], and resorting to NI technology would result in greater mechanical strength, which can be beneficial in withstanding the large stress and forces experienced in a fusion device environment [2021-MIT], and lower coil voltages, a known limiting factor in large fusion machines.

In Europe, within the scope of the EUROFusion DEMO activities, HTS have been specifically considered for the design of HTS inserts of the DEMO central solenoid and TFC winding pack, to extend the coil operation beyond the typical J/T/B range of Nb_3Sn. Similarly, HTS are also being considered for the DTT central solenoid. A notable advance relevant to fusion is the development of twisted-stacked HTS cables, in their various forms and names. These are seen as a promising configuration for HTS fusion Cable-in-Conduit Conductors (CICC). Research is on-going to evaluate magnetization losses in these HTS cables to understand and optimize the performance of the conductors in high magnetic fields. The main challenges are in the complexity of the design, the scaling up these technologies from experimental or small-scale prototypes to full-scale fusion reactor components and the long-term durability and reliability of these conductors under extreme conditions of a fusion reactor, including radiation damage.

As mentioned in the previous section, NI HTS magnets are at the cutting-edge of the development of magnets for fusion devices. In this domain, Tokamak Energy in UK and Commonwealth Fusion Systems (CFS) in US, have been working on the development and testing of NI magnets. The latest results reported by CFS show tests carried out on a NI magnet made of 270 km of REBCO operated at 20K reaching a magnetic fields of 20 T with a 100 MJ of stored energy [2024-HAR]. Although this is a spectacular performance, the robustness against quench could not be demonstrated, and here again we see that a critical step is missing towards large-sale exploitation of this technology.

In the field of stellarators HTS coils can be even more attractive since they operate at constant current, reducing the problem of induced losses by time varying fields an issue to which HTS conductors are especially sensible. On the contrary, the required complex 3D geometries for the coils represent the main challenge to solve. In this sense initiatives like the VIPER cable (a non planar REBCO tape-based cable) [2023-RIV] were successfully carried out on model coils cooled at 77K and reaching critical currents of 5700 A

HTS are really hitting their stride in terms of accessibility, and a big part of that is thanks to increasing demand and the ability to produce more. Projects like SPARC by Commonwealth Fusion Systems (CFS) are leading the charge, pushing bold programs that are opening up new possibilities. This means that HTS, once a niche technology, is now moving towards mainstream use.

The state of the art of HTS in nuclear fusion magnets represents a dynamic and evolving field, marked by significant technological advancements and collaborative efforts. While challenges remain, the potential of HTS to revolutionize nuclear fusion technology offers a promising avenue towards achieving sustainable energy solutions.

Resolving the engineering challenges identified as the main driver of the prototypes included in the scope of EuMAHTS (WP5) is directly relevant and applicable to progress in magnets for fusion devices.

Accelerator magnets

The interest in the potential applications of High-Temperature Superconductors (HTS) for accelerators began to solidify in the mid-2000s both in the European Union and in the United States. The US Department of Energy's (US-DOE) Very High Field Superconducting Magnet Collaboration [2011-TOL] specifically focused on BSCCO-2212 as an HTS high-field conductor. This initiative has now become part of the US-MDP, which encompasses BSCCO-2212 and REBCO, in Rutherford and Conductor-on-round-core (CORC) cables, along with various magnet configurations such as racetrack and canted cos-theta [2016-GOU]. In the European Union, the initial efforts were driven by the interest of a post-LHC collider, undertaken within the frameworks of EU-FP7 EuCARD [2012-DER], EuCARD2 [2018-ROS-1], and EU-H2020 ARIES [2018-ROS-2].

The above EU initiatives, though funded at modest level, allowed the European community of accelerator magnet research to have first-hand experience in HTS and address a few issues. More than 1 km of high-performance tape (J_e > 500 A/mm^2 at 20 T, 4.2 K) has been manufactured and characterized, and a few km were procured from leading manufacturers worldwide. Out of this tape, several 30 m unit-lengths of cables have been assembled and tested up to 13 kA. The cables were then used to build small prototype dipole magnets. These have achieved bore fields ranging from 3 T to 5 T when operating independently[2021-ROS]. These results are only the initial step in a path towards outperforming LTS. The plan is to proceed further, and test the small-size demonstrators as inserts into large bore LTS background dipole magnets. This is similar to what done in the initial steps of development for high field solenoids for science and NMR application, probing the novel realm of fields and associated forces.

QUOTE HERE FIRST USE OF HTS IN ACCELERATORS ? MULTIPOLE MAGNETS IN KOREA, FRIB IN THE US

Objectively, the advances in HTS magnets for accelerators are modest when compared to the other fields of science, quoted earlier. Still, these initial efforts have spurred the interest in HTS options for a future collider, and have entered explicitly among the recommendations emitted by the European Strategy for Particle Physics calling for focussed R&D towards high field magnets, including HTS. The reasons are not only the field reach, but also the possibility to reduce energy consumption and cryogen inventory. This is especially important for any future circular collider, whose scale, cost and electrical power is likely to exceed that of any of the accelerators built so far. This is why HTS magnet R&D feature prominently among the priorities of a muon collider [2023-MUC], the hadron-hadron future circular collider FCC-hh [2019-FCC] and the Super Proton Proton Collider (SPPC) [2015-AHM].

In fact, the interest in HTS magnets has recently developed specifically for applications where energy consumption is limiting. This is the case of accelerators, beam lines and experiments built with large resistive magnets, whose resistive power can easily peak at several hundreds of kW and HTS magnet technology offers a significant reduction. Similarly, energy consumption is of concern in applications where high heat loads originate from decay and radiation, such as accelerator for radioactive nuclei. Finally, cryo-coolers based HTS magnets are of interest for areas where access to liquid helium is difficult, or not possible.

Although the prototypes defined within the scope of EuMAHTS are solenoids (WP6, WP7) and undulators (WP8), the technology developed (WP5), the fact of addressing operation at temperature above liquid helium, and the management of large stored energy, as is often the case for accelerator magnets, are all factors that will contribute positively to advancing HTS accelerator magnets research.

Undulators for Light Sources and FELs

Undulators, a series of dipoles with rapidly alternating direction, are a key component in synchrotrons and free electron lasers (FELs) to produce highly brilliant X-ray photon beams, which are used for research in physical sciences and engineering and serve a vast scientific community. Most light sources make use of undulators based on permanent magnets, the present state of the art [REFERENCE].

The main direction of development is towards high magnetic fields while decreasing the period of the undulators. The small period allows to reach higher photon energies for the same electron beam energy, and therefore more compact and sustainable accelerators. The high magnetic field is essential for the tunability of the photon energy. These features are even more relevant for FELs, since they also imply a decrease in gain length. High-field/short-period undulators (order of 2 T and 10 mm), reaching K=2, would enable lasing at unprecedented high photon energies above 50 keV in FELs, necessary for studying processes with time scales as small as femtoseconds and happen in sample environments difficult to access. Relevant examples are high energy density science to study planet evolution, or in-situ microscopy on technological processes, such research on welding or electrical batteries [2023-CAS].

With roots tracing back to pioneering efforts in the late 1970s, ongoing research and innovation have propelled superconducting undulators (SCUs) to be commercially available and successfully in use in modern light sources [2022-ZHA]. Such SCUs are based on NbTi and, for the same beam stay clear and period, reach more than 30% magnetic field increase with respect to permanent magnet undulators, mainly for periods above 15 mm. An exceptional magnetic performance can be reached by using HTS tapes instead of NbTi wires. Reaching magnetic fields of the order of 2 T with periods below 15 mm for a beam stay clear of 5 mm would double the magnetic peak field on axis with respect to the most advanced permanent magnet undulators and increase by more than 50% with respect to the NbTi SCUs.

Unlike traditional permanent magnet (PM) undulators, SCUs boast the ability to adjust magnetic field amplitudes by modulating transport currents, eliminating the need for bulky mechanical structures and expensive components. This innovation not only enhances operational flexibility but also significantly reduces costs associated with undulator construction and maintenance.

Furthermore, SCUs exhibit lower sensitivity to radiation compared to PM undulators, mitigating concerns related to irreversible demagnetisation induced by beam losses. This advantage is particularly crucial for free electron lasers (FELs) powered by high repetition rate superconducting linear accelerators (LINACs) and diffraction limited storage rings (DLSRs) with stringent requirements for beam stability and reliability.

As we are moving towards fourth-generation synchrotron radiation facilities and new FEL beamlines, the demand for advanced undulator technologies has never been greater. SCUs play a pivotal role in meeting these evolving needs by offering unparalleled beam brightness and spectral control together with the potential of a democratization of light sources, making them more compact and sustainable. Moreover, their versatility makes them indispensable for optimising beamline performance and facilitating ground-breaking scientific research across various disciplines.

In conclusion, HTS based SCUs represent a paradigm shift in undulator technology, offering unmatched magnetic performance. As research and development efforts continue to push the boundaries of what is possible, HTS based SCUs will remain at the forefront of innovation and will be crucial to reach more compact, cost-effective light sources at disposal of a larger community helping to solve major societal challenges as energy transition, climate change, health and environment.

The prototype undulator (WP8) planned within the scope of EuMAHTS addresses the above challenges and will provide direct demonstration of performance requested for the next step in light source and FEL next step in analytical power.

Medical applications

Modern healthcare critically depends on magnets for diagnostics, in MRI machines that offer a unique non-invasive imaging possibility, and particle therapy, profiting from the superior performance of electrons, protons and ions compared to X-rays for cancer treatment. Indeed, superconducting magnets are established technology for the applications above, but they are presently relying on the use of Nb-Ti. To date, HTS is not used for either field of application. But HTS can offer benefits in terms of augmented performance, smaller size, and simplified engineering and operation. This is why HTS, and in particular REBCO, is the baseline for the next step in research MRI, with a 14 T project recently funded at Radboud University, in The Netherlands [2023-RAD]. This new scanner will offer new possibilities of research in brain disorders, medicine and neuroscience, well above present capabilities represented by the ISEULT 11.7 T full-body MRI recently commissioned at Neurospin, Saclay (FR). Although ultra-high field MRI will remain a market of modest size, with only a few such systems worldwide, this research realization will be the first large scale use of HTS in MRI, and may pave the way for wider application mostly motivated by the potential of reduction in size and simplification of medium (3…7 T) field machines.

The same motivation, more compact and simpler machines, applies to the use of HTS for particle therapy. HTS magnets with higher field than resistive or LTS magnets, and operating at temperature higher than liquid helium, are under study [2021-IFA]. Particular interest is devoted to ion synchrotrons and gantries, where HTS can lead to a reduction of a factor two of the size of the installation, with considerable benefit for the societal penetration of this advanced cancer treatment that is still largely unexploited.

The technology developments and prototypes proposed in EuMAHTS, in particular efficient cryogenics and heat transfer (WP5), winding of REBCO in complex 3D geometries (WP5) and the management of large forces and storage energy in the split solenoid demonstrator (WP7) are directly relevant to the development of superconducting magnets for healthcare.

1.1.3 TRL levels

The description of the state of the art of HTS magnet technology in the various fields of application indicates that the Technology Readiness Level (TRL) has a very broad spectrum. The most advanced TRL is for NMR, where there are now industrial products that, although still in the first years of market penetration, are commercialized for user applications (i.e. TRL approaching 8 to 9, with *complete systems operating as user instruments, though in an effectively non-competitive environment*). These systems rely heavily on established superconducting magnet engineering and technology, which also explains why their TRL is so advanced. The next step in HTS magnet technology, on the other hand, is much less advanced. Record fields have been attained, e.g. with NI windings, spectacular achievements, but also pointing to a number of crucial issues to be resolved. These realizations were possible on laboratory scale, beyond the proof of principle, but not much more advanced than TRL 3 to 4, corresponding to *laboratory realizations that have proven experimentally the concept and are typically built and operated in controlled environments with large usage of resources and expertise*. In this case, however, achieving TRL that would allow elicit strong industrial interest, so TRL 5 to 6 with *prototypes that demonstrate manufacturing and operation in industrially relevant environment*, would make a significant difference in the market, and a quantum step for technology.

The main aim of EuMAHTS is to achieve an increase of TRL in HTS magnet technology, from laboratory concepts and technology TRL of 3 to 4, to a level that would allow entering the horizon of industrial exploitation, i.e. TRL of 5 to 6.

1.1.4 Next Step

We can identify commonalities in the state of the art and future plans among the various fields of application discussed above. Common technology goals can be found in various aspect of magnet performance (field and volume), operating margin (engineering current density), mechanics (stress and strain on the conductor), protection (stored energy and energy density), capital and operation expenditure of a magnet system. Examining the above parameters, we have identified four *grand magnet challenges* that represent well the desirable next step for the various fields of application listed earlier:

- Ultra-high field (UHF) and compact HTS solenoids, field range of 40 T and higher, with small bore, in the range of 50 mm for materials and life science and high energy physics applications. Magnets of this class have engineering current density well above 500 A/mm^2, stored energy in the range 500 kJ and energy density up to of 300 MJ/m^3. The conductor needs to sustain electromagnetic stress up to 600 MPa. Such magnets are of interest for material science in high magnetic field, UHF NMR for life sciences, and high energy physics experiments such as a muon collider. Field reach is the most relevant performance indicator for this class of magnets, and limits are expected to be dictated by stress and strain, as well as quench management at high current density and energy density. In addition, aspects of field quality and field persistence are critical qualifier for a good magnet of this class.

- High field (HF), HTS solenoids, with field range around 20 T, and large bore, in the range of 1 m diameter for fusion and high field science applications. With a stored energy of several hundreds of MJ, magnets of this class tend to be driven by structural (stress) and electrical engineering (voltage) limit. As such, they are likely to be conceived with modest engineering current density, below 100 A/mm^2. Energy efficiency, on the other hand, is crucial in systems of such size and cold mass, with target operation at cryogenic temperatures well above liquid helium, e.g. 10 to 20 K. System cost and energy efficiency are the most relevant performance indicators for this class of magnets, and optimal design is a balance among field performance, structural limits, quench management and cooling.

- HTS dipoles and quadrupoles, with a broad range of peak field, from modest values (a few T) to high values (20 T and higher), magnet bores in the range of 50 mm to 250 mm diameter, and length scale from one meter up to ten meters. At the high end of the performance range, these are the magnets that could enable affordable and sustainable future colliders such as a 100 TeV FCC-hh or a 10 TeV muon collider. Similar technology would also provide a robust and low energy consumption solution in the range of low to medium field, profiting nuclear physics, light sources, medical accelerators and ganties, and industrial accelerators. To be cost-effective and energy-efficient, this class of magnets would require high current density, ideally reaching 800 A/mm^2, and operate at temperatures well above liquid helium, e.g. 10 to 20 K. Similar to ultra-high-field solenoids described earlier, the combination of high field and high current density implies high mechanical stress and energy density, with values comparable to those quoted earlier. In this case, in addition, the stored energy is also large, in the range of tens of MJ, while the winding requires mastering 3D shapes. The most relevant performance indicators for HTS accelerator magnets, beyond field and aperture, are related to compactness, cost and energy efficiency, while limits will be dictated by stress and strain, quench management, and efficient heat removal. Also in this case field quality is a critical qualifier of the magnet goodness.

- High field HTS undulators and superbends, two classes of magnets special to light sources that share the need to generate sharp field variations over short longitudinal distances. A challenging target for undulators is achieving a field of 2 T in the gap, with short period, 10 mm, and a gap of 5 mm, which corresponds to a K value of about 2. COMMENTS ON SUPERBEND ? Achieving such parameters is important to increase the analysis reach of light sources and free electron lasers. Achieving the desired K value with suitable and stable field quality is the main performance indicator for this class of magnet, while limits are imposed by the engineering of the winding, mechanical support, joints and cooling. ADDITIONAL QUANTIFICATION ?

A pictorial of these grand challenges for the next step in HTS magnet technology is shown in Fig. 3, where we report the bore field vs. bore size of magnets. We are aware that this representation is only a partial view, based on a selected couple of performance indicators, while hiding the rest. The field range and magnet dimension of the four challenges covers a large parameter space. We are hence confident that our analysis truly covers the whole frontier of HTS magnet technology.

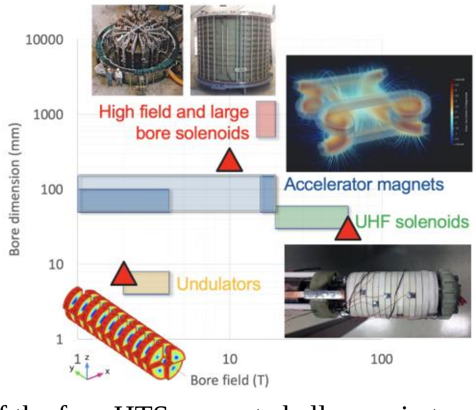

Figure 3. Schematic representation of the four HTS magnet challenges in terms of magnet bore dimensions vs. bore field. Relevant design and magnet examples are shown to give an impression of the technology. Also reported the performance targets for the prototypes proposed within the scope of EuMAHTS (triangles).

1.1.5 *Engineering Focus Areas*

Based on this analysis and the above narrative we can identify four *engineering focus areas* that are critical for all challenges in the future of HTS magnet technology:

E1. High engineering current density, targeting the range of 800 to 1000 A/mm^2 at 20 T, and 500 A/mm^2 at 40 T. is the range required to make HTS magnets affordable for large installations such as a particle accelerator, where the material cost is a driver, and corresponds to a factor two higher than present state of the art. High engineering current density also applies to compact gradient magnets such as undulators, where the required field gradient needs high current in the vicinity of the magnet bore.

E2. Operation under high strain and stress, with tensile stress values up to 800 MPa and compression stress values up to 400 MPa. These values of stress are a direct result of field and current density in compact windings. In reality, the stress field is more complex than two simple components, and we are aware that internal tensile and shear stresses can be even more critical. In general, the challenge will be to design and operate in the conditions where the fragile superconductor will be in close vicinity to its mechanical limits. This regime cannot be reached with other high field superconductors, whether the LTS Nb_3Sn, or the HTS BSCCO-2212.

E3. Quench protection at high current density, quoted earlier, and large stored energy density, up to 300 MJ/m^3. In this range of values, a standard protection is no longer possible, because the temperature in the quenched region rises too fast for standard voltage-based detection and quench dump methods.

E4. Operation at temperature significantly higher than liquid helium, ideally in a regime where other cryogens become an option for cooling. The first such temperature is 20 K, although this choice is rather arbitrary. Operation at high cryogenic temperature implies gaining mastery of conditions that are not standard practice for helium cooling, finding the best refrigeration cycle, and devising efficient means to extract the heat from the coil winding, up to the cold source. This is a significant change in paradigm, especially for large systems such as particle accelerators and fusion machines that rely on large quantities of liquid helium as thermal buffer and vector.

The principal focus of EuMAHTS is set to respond to the four engineering focus areas, and seek whether HTS magnets be engineered, built and operated to accommodate the exceptional requirements detailed above, or provide the actual performance limit of the technology should this not be the case. As we have mentioned already, other matters are also of importance to the success of HTS magnet technology. Examples are field quality and persistence, winding technology for 3D shapes, cables and joints. They will be considered in the definition of the studies, technology support and engineering of the prototypes built and tested within the scope of EuMAHTS.

#§PRJ-OBJ-PO§#

1.2 Methodology #@CON-MET-CM@# #@COM-PLE-CP@#

EuMAHTS is structured as a project, divided in work packages that address various aspects of the proposed activities, under a governance reporting to the EU authorities. The structure of the project is shown graphically in Fig. 4.

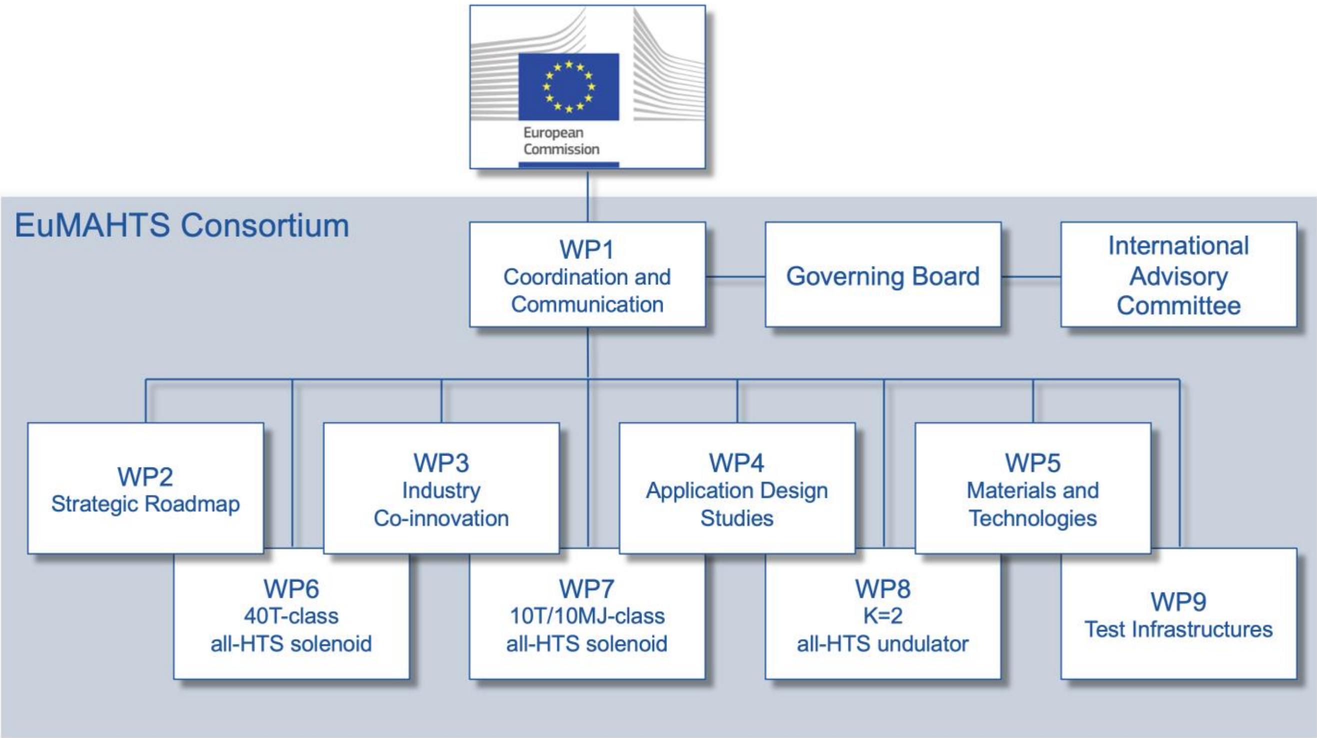

Figure 4. Structure proposed for the organization of work, management and governance of EuMAHTS.

We describe below the main principles and choices that have led to the proposed structure, expanding then on the project coordination, governance, their functions and inter-relation.

1.2.1 Advancing TRL through prototyping

As we have anticipated, a key objective of EuMAHTS is advancing TRL of HTS magnet technology by two units, to make this technology ready for industry to pick-up and carry further. We believe that this is best done by designing, building and testing practical prototypes that address the engineering challenges identified earlier. Prototypes are central to EuMAHTS, they will act as catalysers of our efforts, and provide the focus required to address the extraordinary challenges at hand. The prototypes selected in our proposal will be tested *in field*, to show that they can provide advanced capability in the specific field of science. In fact, if successful as we anticipate, we can foresee that all of them will become first-of-a-kind for new high-level research infrastructure, giving access to new research possibilities.

The prototypes proposed within the scope of EuMAHTS are the following (see WP6, WP7 and WP8, described later):

- An all-HTS ultra-high field solenoid targeting a field of 40 T with a minimum 50 mm bore. This solenoid is a demonstrator towards a UHF test facility, the final cooling of a muon collider, and provide useful test bed for next generation UHF NMR. The technology is relevant for multiple other fields of application, requiring management of large stress and strain, and energy density. This prototype addresses mainly the engineering focus areas E1, E2 and E3;
- An all-HTS standalone solenoid (split coil) with a field target of 10 T, a minimum 400 mm bore, large stored energy, target of 10 MJ, and operating at high cryogenic temperature, in the range of 20 K. This solenoid could provide the background field for a new test facility for testing RF components, and the split would be relevant technology for high energy physics (muon collider) and medical applications (SC cyclotron coils), neutron scattering instrument in a beam line. The high stored energy and energy density (compact coil winding) are relevant for large size systems such as MRI, or coils for magnetically confined fusion. This prototype addresses all the engineering focus areas: E1, E2, E3 and E4;

- An all-HTS small period undulator with 2 T gap field, 10 mm period and 5 mm gap, with K=2. This HTS demonstrator would produce field gradients well beyond the state of the art, as required for next generation synchrotron light sources and FEL. This prototype addresses mainly the engineering focus areas E1, E2 and E3.

1.2.3 Choice of REBCO

Amon all technical HTS, namely REBCO, BSCCO and IBS, the material with highest performance is REBCO. Following the review of the state of the art outlined earlier, REBCO is presently the material of choice for all fields of applications. Also, the cost per unit length and carried current, the metrics of relevance for magnet technology, is the lowest among all HTS. In fact, the cost per kA m of REBCO at 16 T and 4.2 K is presently lower than that of Nb3Sn, which is a very suggestive fact. In addition, among all HTS, REBCO has still headroom for improvement, especially in terms of mechanics and resistive properties (critical current is already above values required for high field magnets). Finally, there is in the EU a considerable basis of expertise and research infrastructure (KC4, a research infrastructure for coated conductors fruit of a KIT-CERN collaboration, part of EuMAHTS) and an industrial REBCO producer (THEVA).

Above are the reasons why EuMAHTS focusses on REBCO as the material of choice to develop HTS magnet technology.

1.2.4 Need for concepts and technology

Optimal use of HTS in magnet technology requires a paradigm shift in design and manufacturing. Design, manufacturing and operation of HTS magnets will no longer put the accent on margin: training will likely be absent. At the same time, mechanics and quench detection and protection will be very challenging, much beyond what we know from LTS. NI HTS coils are an attractive approach, but their engineering and manufacturing is far from being common practice, requiring novel ideas, e.g. for transverse resistance control. And the fact that REBCO comes in the form of tapes requires an innovative approach to making cables, when required, and coils.

Addressing the above challenges will need significant advances in magnet science and technology, developing concepts, characterizing materials and testing small samples in *unit scale* before implementing novel solutions in the prototypes. This is why EuMAHTS has identified critical technologies, whose development will run in parallel with the engineering of the prototypes. A full-fledged development program, attacking the multiple aspects of HTS magnet engineering, construction and operation would largely exceed the scope of EuMAHTS both in resources and time. This is why we have intentionally restricted developments to critical area, where technology development is either mandatory (e.g. cryogenic cooling, joints, quench management) or would have a measurable positive impact (e.g. conductor mechanical properties, radiation resistance) on the outcome of the prototypes.

1.2.5 Industry co-innovation actions

A strong involvement of European industry is mandatory to ensure that European Research Infrastructures remain at the forefront of their respective scientific fields, and offer the best service to their user communities. This is especially relevant in a young field of technology such as HTS magnets, and it is the main reason why EuMAHTS implements a dedicated program of *co-innovation* with industry, with significant allocated funding, of which the largest part is dedicated to supporting directly the industry contributions. Thanks to EuMAHTS co-innovation, European industry will be involved from the very beginning on priority research work (see WP3, described later).

A *co-innovation action* in EuMAHTS is considered as an activity where industry and research institutes collaborate since the earliest stage of the technical concepts to implement specific research and development relevant to the objectives of EuMAHTS, at the industrial premises, including the tools and methods required to achieve the desired result. The research institutes and universities provide continuous support and follow-up, experimental background, and access to facilities. This pursues programs initiated in the last years on coordinated and innovation actions such as AMICI and IFAST, but represents one step beyond in terms of maturity of links with industry.

A basic requirement for the selection of co-innovation actions is that they refer to priority research at low TRL. Indeed, the idea of co-innovation is to profit from industrial methods and experience to progress in TRL, thus contributing to the success of EuMAHTS. The benefit, if possible, to the engineering and construction of the prototypes will also be taken into account. Co-innovation actions must have potential to generate immediate return to industry, contributing to the promotion of the innovative potential for industrial exploitation of the technical concepts. This implies increased EU industrial capability in the novel field of HTS magnet technology. The profile of the industry targeted in this co-innovation program spans from consolidated magnet component related companies to deep-tech spin-offs small enterprises.

The co-innovation actions pre-selected in EuMAHTS are transversal to several fields of application. Our initial analysis, conducted jointly with industrial actors in a number of meetings and consultations that took place in the preparatory phase of this proposal, has identified themes of specific interest to High Energy Physics and Nuclear Physics, Light Sources and Free Electron Lasers, and Fusion. Three general areas for co-innovation have been identified: HTS Magnet Production, HTS Magnet Cooling and HTS Magnet Powering. The potential topics are listed below, noting that this is only a starting point, to be reviewed as part of the first activities of WP3:

- *HTS Magnet Production*
    - HTS cables for complex topologies (main application: Fusion, industry, Particle Physics)
    - Delaminated HTS for Magnets & Cables (main application: Fusion, Particle Physics, industry)
    - Winding Technologies for HTS magnets, including Undulators (main application: Light sources)
    - Energy saving HTS beam transfer magnet (main application: Nuclear Physics, Medical applications, energy, transport, others)
- *HTS magnet cooling*
    - Exploring a new cooling concept for cooling HTS magnets (transversal applications)
    - Centralized Cooling Systems for energy-efficient HTS Magnets (transversal applications)
- *HTS Magnet Powering*
    - DC/DC Converters at Cryogenic Temperatures for HTS Magnets (transversal applications)
    - Prestress and Current Injection System for non-insulated HTS coils (transversal applications)

Though the specific topics of co-innovation actions to be implemented have not yet been defined, nor the industrial partner implementing them, the specific method for selection of action, market survey, request for proposals, bidding and adjudication has been thoroughly examined and defined. Below we describe the proposed method.

Selection of co-innovation actions

The selection of the most suitable actions, among the ones above or additional options agreed during the internal review of co-innovation actions, will be an outcome of EuMAHTS, and will be based on the following criteria:

- technical quality of the proposal;
- largest contribution to increase the overall EU industry capability;
- largest impact on TRL increase;
- largest added value for the field of HTS magnet technology;
- the transversal nature of the co-innovation action (technology serving more than one community);
- the acceptance of IP-share rules compatible with the R&D nature of the activity;

- available funds.

An Internal Selection Committee (ISC) will be created for this purpose. The ISC will be composed by a representative of each of the partners participating to the proceedings of WP3, and one member of the Project Office appointed by the Project Coordinator. This committee will be chaired by the WP3 Leader. Decision will be taken following a consultation process that will include industry, to confirm the potential interest of the industrial sector and availability of companies to participate. Industry contacts are guaranteed via the AIPF (the Accelerator Industry Permanent Forum, a high-level industry-academia interaction body constituted in 2023), pursuing activities initiated during the preparatory phase of this proposal. Selection will be based on a two-thirds majority of the votes cast from a quorum of at least two-thirds of the committee representatives. Arbitration rights will be given to the WP3 leader and the member of the project office appointed by the Project Coordinator. Written minutes will be edited to document the complete process, and will be attached as an Annex in the deliverable document D3.1.

Form for involvement of industry

For the format of the involvement of industry we have considered various aspects:

- the R&D nature of the subjects to address;
- the fact that in most cases more than one company may be interested on taking part;
- that the proposed structure of the co-innovation implies joint development with research institutes at the early stages (i.e., a co-design), while industry will take over responsibility for development once concept and design are clear, remaining in close contact with the research institutions.

To match the requisites above, as first approach, we have decided to engage industry through the Pre-Commercial Procurement (PCP) mechanism. The WP3 leader will take the role to develop and place a number of PCP contracts, one per action. We recall that EuMAHTS partners have previous experience on participating on this type of innovation procurement, both at European and national levels.

Market survey

We have planned a market consultation that will take place prior to placing contracts. This is very much advisable to make as the most efficient way to define and adapt the contract procedures to the actual situation of the industry capability. We will use as template the market survey format followed in the last PCP tenders where EuMAHTS partners has taken part in the last year. This market survey will be done with the help of AIPF and ILO (national Industry Liasson) offices.

Advertising and publication of action calls

We will advertise the selected co-innovation actions in full transparency, ensuring the widest possible dissemination of information. Following the national applicable laws, the action calls will be published in the EU tender Portal. In addition, advertising will take place through the communication channels provided by the industry boards of our communities, in particular via the ILO offices of the WP3 partners' countries, together with the available industry associations, such as INEUSTAR (ES), PIGES (FR), BSSE (SE) or BSDK (DK), CONECTUS (EU).

Tendering process and contracts

Adjudication of contracts will be based on the responses to the open action calls, ranked by the ISC. The selected company will be granted a contract, following the PCP requirements. The contracts will be formalized following the procedures imposed by the Spanish Public Sector Contracting rules. This guarantees compliance with EU rules, and the highest standards in terms of fair contractual conditions, compatibility with the nature of the object of the development, right pre-requisites for the bidding companies, proper advertisement of the calls, transparency, equity and legal compliance.

The Contracting Offices will support the EuMAHTS team on these procedures. Before placing the contracts, these procedures will be audited by the Legal Departments of the partners. We are aware that this procedure will require a certain time, and this has been taken into account in the project planning. We believe that this overhead is necessary to ensure compliance with legal terms for the contracting procedure and a fair relation with Industry.

Subcontracting

The funds reserved for the co-innovation program are included in the project budget for subcontracting. Besides, it is expected that a company expert on innovation procurements will be subcontracted to provide support to work the PCP contracting procedures and follow up efficiently, specifically, to define contract rules as simple as possible and with conditions adapted to the actual needs of the co-innovation program.

Intellectual property (IP) (under review)

The IP generated in the co-innovation actions must be shared among all the EuMAHTS partners and available, under certain restrictions and priorities, to the whole HTS community. For the sake of efficiency, the project will rely on a representative member to manage on their behalf the IP aspects during the project. The commitments agreed on IP will remain valid for 5 years after the conclusion of the project.

Before initiating the program, the project will confirm that, for each action finally selected, there is no previous background of the proposing research institution or any third party that may block the IP policy agreed upon in this WP.

These terms will be collected in the Grant Agreement before initiating the program.

1.2.6 Structure of the project and inter-relation of work-packages

EuMAHTS has been structured in nine work packages (WP). The function and roles in the work packages is described below, and a schematic representation of their inter-relation is shown in Fig. 5.

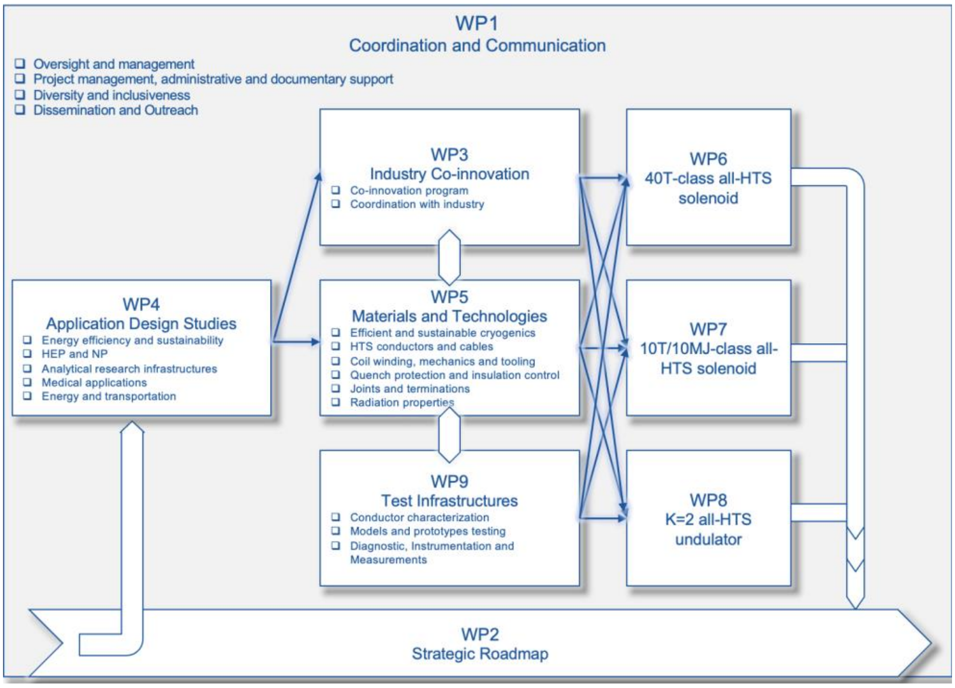

Figure 5. Schematic view of the inter-relation of work packages within the scope of EuMAHTS.

WP1 – Coordination and Communication. This work package encompasses all aspects of project management, administrative and documentary support. We have included in WP1 the dissemination and outreach actions, ensuring wide exploitation of the results, as well as gender dimension and inclusiveness. WP1 operates under the leadership of the Project Coordinator (PC) and Co-Coordinator (PCC). PC and PCC report to the EuMAHTS Governing Board (GB) and to the EU Authorities.

To act in practice in all above aspects, EuMAHTS will appoint a Project Management Officer (PMO), an Administrative and Documentary support Officer (ADO), a Dissemination and Outreach Office (DOO) and a Gender and Inclusiveness Officer (GIO). Together with the PC and PCC, they will form the Project Office (PO) that will meet regularly (typically once per month) to act on the follow-up on all administrative and control aspects of the execution of EuMAHTS.

The PCC and PCC also co-chair the Technical Coordination Meeting (TCM), formed by all WP Coordinators (WPC), the Chair of the Governing Board, and ad-hoc invited experts from within the project, e.g. the Task Leaders (TLs) and Deputy Task Leaders (DTLs), as well as external experts, if necessary. The TCM will meet regularly (typically once every two months) to review and follow-up on all technical aspects of the execution of EuMAHTS.

WP2 – Strategic Roadmap. The scope of activities for this work package is to develop an inclusive strategic roadmap for HTS magnet technology that matches the needs of the various fields of activity represented in the project. The roadmap will also provide guidance for the industrial exploitation of the results of EuMAHTS beyond the completion of the project.

WP2 will collect, integrate and unify strategic demands from High Energy Physics (ESPP-2022, P5-2023), nuclear and astro-particle physics, synchrotron and FEL light sources (LEAPS), neutron scattering , the European Magnetic Field Laboratory (EMFL-Isabelle), fusion initiatives (including the private EU sector), health care, and industry. Excellent strategy documents, referring explicitly to the need of HTS magnet technology, are available for several of the fields of application listed above. Examples are given in the references collected so far [2022-LDG], [2016-GOU], [2018-LEA], [2005-NAS], [2013-NAS]. These, together with the results of previous EU programs (FP7-EuCARD, FP7-EuCARD2, FP7-EuroTapes, H2020-ARIES and H2020-IFAST) will be the starting point of the activity of WP2.

WP2 also reaches out to key players such as EUROFusion, societies such as the European Society of Applied Superconductivity (ESAS), the IEEE Council for SuperConductivity (IEEE-CSC), and the Cryogenic and Superconductivity Society of Japan (CSSJ), as well as consortia such as Conectus, FuSuMaTech, and the Superconductivity Global Alliance (SCGA).

This initial information and consultation process will provide key information on challenges and strategic directions, To perform the planned work, WP2 will initiate and maintain a Strategy Forum, including all participants and invited external actors, to identify opportunities, challenges, and means to facilitate and increase HTS penetration in the different fields of application. The Strategy Forum will promote knowledge sharing on HTS technology within EuMAHTS and among various fields and promote a quicker path towards maturity. The analysis work stemming from the proceedings of the Strategy Forum will be summarized in a EuMAHTS White Paper that will be presented for discussion in a HTS Strategy workshop of wide attendance. The EuMAHTS White Paper and feedback from the workshop will form the basis for the editing of a Global HTS Roadmap.

The intention of the Global HTS Roadmap is to provide a general frame that can be customized for each field of application and sent to the respective governing bodies. Internally, the roadmap will provide a solid framework for the targets and results of EuMAHTS, i.e. the validation of the starting point for the application studies (WP4), materials and technologies (WP5) and the prototypes (WP6, WP7, WP8). At the same time, the context generated by the roadmap will be crucial to identify and promote investments and industrial exploitation (WP3). Externally, the Global HTS Roadmap produced by WP2 will provide input to higher level strategic processes in Europe, and most likely worldwide.

The core activities of WP2 will be completed well in advance of the project completion with the delivery of the Global HTS Roadmap to the EU Authorities and other relevant governance bodies. This will give sufficient time to initiate the implementation of the recommendations. We plan active participation to strategy discussions in relevant fields of application, and lobbying actions to promote the implementation of the roadmap in each community. Specifically, we aim at influencing the next update of the European Strategy for Particle Physics (ESPP) that will take start in 2025 and last about two years. An event will be organized in collaboration with industry (WP3) to favour the exploitation of HTS developed under EuMAHTS and other programs such as H2020-IFAST. The main focus of this event will be on the impact of HTS on society, namely in the field of green energy and healthcare, favouring the involvement of Industry.

WP3 – Industry Co-Innovation. Activities in this work package are directed to support early and active participation of European industry to the innovation process driven by EuMAHTS, as described earlier. After an initial review of co-innovation actions, to ensure the selection is best matched to the objectives of EuMAHTS and the needs of EU industry, WP3 will host the activity of market survey, call for proposals, contract adjudication and follow-up. We recall that we will resort on the EU PCP mechanism for these contracts. The technical follow-up will be performed in collaboration with the technical actors of the other work packages and in particular materials and technologies (WP5) and prototypes (WP6, WP7, WP8).

A second goal of WP3, related to the exploitation of the results, is to advance in the consolidation of a reliable and stable link with the industry related to HTS for EU Research Infrastructures. Setting out an operative contact point with the industry has been declared a limitation in general terms, but more importantly for a co-innovation strategy. WP3 will devote resources to constitute an HTS industry board. To assure an efficient work, the activity will be coordinated with the recently created Accelerator Industry Permanent Forum (AIPF) and the League of European Accelerator-based Photon Sources (LEAPS) industry board. Contacts with boards in other sector in which HTS magnets may be applied will be fostered. This will avoid the spread of representing boards, facilitating at the same time an efficient link with the already operative industry boards in the consolidated instrumentation communities. To guarantee a proper coordination, one of the co-chairs of AIPF will oversee this task. The result of this work will feed into the EuMAHTS strategic roadmap (WP2).

It is very important to remark that the scope and actions proposed in WP3 is fully in line with the European High Field Magnet (HFM) Board strategy coordinated by CERN and participated by the main research institutions in Europe involved on superconducting magnets R&D.

WP4 – HTS Magnets Application Studies.

This work package addresses the potential and challenges of HTS for magnet applications. Focusing on performance, energy efficiency and sustainability, it explores innovative concepts and assesses the impact of HTS in diverse applications such as energy and transportation, healthcare, physics and magnetic-field based research and analytical techniques. Based on our initial considerations, and receiving input from the strategic roadmap of WP2, the results of WP4 will feed with more precise engineering targets both the development of technologies (WP5) as well as the realization of the prototypes (WP6, WP7, WP8). The results of this work package will also feed into the quantification of HTS potential as game-changing technology, to be considered in the development of a strategic roadmap (WP2). Collaboration through HTS design meetings and workshops will position European laboratories and industry at the forefront of the global HTS race.
The tasks identified will cover the following fields of study:

- Energy efficiency and sustainability, looking in opportunities for lowering consumption, reducing operating risk and improving availability of research infrastructures using HTS magnets, considering the effect of operating temperature, cryogen type and inventory;
- High Energy Physics and Nuclear Physics applications, an analysis of the new opportunities in these fields of research that typically need large research infrastructures. The demand for augmented physics potential offered by HTS magnet technology needs to match societal acceptance and long-term sustainability;
- Light Sources and FEL applications, a conceptual study of HTS undulator magnet technology to extend the analysis potential and fields of application of this technique, thanks to higher energy, intensity and quality light;
- High fields as an analysis tool, looking into how the potential of ultra-high-field HTS magnets can be realized for materials and life sciences such as quantum materials, electronic properties, proteomics, neutron scattering experiments, where novel magnet technology is the only means to extend the field of research;
- Medical applications and healthcare, considering the effect of HTS magnet technology on therapy

machines using charged particles, beam delivery systems such as gantries, and research MRI systems. Smaller systems with improved performance are expected to improve the penetration of these advanced therapy and diagnostics means in the society;

- Energy and transportation, focussing on HTS magnets for energy production (fusion, generators) and mobility (motors), where a new technology could accelerate the energy transition.

WP5 – Materials and Technologies. Success in HTS magnet engineering depends critically on advances in specific area of material science and technology. This work package groups the activities devoted to targeted R&D on materials and manufacturing solutions selected in our initial analysis:

- Cryogenic heat transfer. Heat transfer in regimes other than liquid helium requires characterization and testing before engineering solutions can be finalized and effectively implemented. We plan to test samples in support to the prototypes, based on the selected cooling mode (direct, indirect, gas, vacuum, etc);

- HTS cables and conductors. This task maintains coherent performance specification and acceptance troughout the project. Conductors with multiple tapes are studied as means to increase robustness against degradation, to decrease inductance, and ease protection. We foresee the need for improvements in the mechanical and resistive properties of HTS, which is presently the true limitation to achieving and boosting performance in HTS magnets. Tailoring industrial production to improve such performance is not a realistic goal. EuMAHTS will profit from the unique European research infrastructure KC4, built at KIT in collaboration with CERN, to explore means to improve internal adhesion and control electrical resistance among the micro- and nano-scopic layers in a REBCO tape. Finally, activities will be devoted to examine and test means of reducing AC loss in cables, to allow for energy efficient pulsed applications;

- HTS winding technology, mechanics and tooling. REBCO comes in the form of tapes, and winding in any form, but especially non-planar configurations, still require development of coil shapes and tooling. Experiments will be done to see how to best produce the desired winding shapes. Choice of geometry (e.g. single pancakes, double pancakes, layers), insulation (e.g. dry, impregnated, soldered), structural support (e.g. reinforcement, pre-compression) and other variants produce final mechanical and thermo-physical properties in a wide range of values. Characterization tests will identify the variants that best match the requirements for the prototype magnets, and in general HTS magnet technology.

- Quench detection and protection, which is defined as an activity of its own given the extraordinary challenges. Unit tests in stacks and small coils with extensive instrumentation are planned to provide insight in initiation and propagation of quench, in particular in NI coils, to yield relevant values of characteristic times for magnet design, as well as a validation basis for simulations.

- Joints and terminations, an activity devoted to the selection and validation of the configurations providing sufficient electrical performance, mechanical robustness, as well as ease of fabrication and integration in the magnet.

- Radiation properties and radiation hardness. Many of the applications listed earlier are associated with radiation dose. HTS materials have known sensitivity to radiation, but the damage mechanisms are not fully understood. It will hence be important to follow developments, if applicable define and execute experiments, and integrate results in the magnet design.

We expect this work package to be a central link between strategic goals (WP2), the quantified challenges of the application studies (WP4), and feedback from the construction and test of the prototypes (WP6, WP7, WP8, WP9). Technology development is one of the subjects of industry co-innovation (WP3). The materials and technology WP5 will provide a practical means to ensure efficient exchange of information among the multiple actors and diverse focuses in EuMAHTS.

WP6, WP7, WP8 – Prototypes. The prototype work packages host the resources and activities to perform the engineering design, construction and testing of the three EuMAHTS prototypes described earlier:

- WP6: All-HTS ultra-high field solenoid, 40-T class, 50 mm bore, length of the order of 100 mm. This is a very compact winding magnet, with high engineering current density, stress and strain, and stored magnetic energy density. Challenges are the field performance, mechanics and quench management. This prototype magnet, after successful test, could be used as a test bed for material properties in UHF conditions rarely accessible to EU researchers. It is planned to host the prototype at CERN;

- WP7: All-HTS split solenoid: 10T-class, 10MJ-class, 300 mm x 200 mm room temperature bore. The magnet will be operated at high cryogenic temperature (range of 20 K), either dry- or gas-cooled. Challenges for this magnet are mechanics and quench management, because of the large stored energy, as well as efficient operation at high cryogenic temperature, with sufficient operating margin. The magnet will be designed to be powered both in parallel and anti-parallel excitation mode, providing either uniform field or very high field gradient. This prototype magnet, after test, will be used as a background field facility for testing accelerator and detector components, such as the RF cavities for the Muon Collider cooling cell. It is planned to host the prototype at INFN;

- WP8: All-HTS K=2 undulator, with 2T gap field, 10 mm period and 5mm gap, as a prototype for the next generation synchrotron light sources and FEL. This prototype will enhance the magnetic field strength by a factor two with respect to NbTi, at similar period length and gap width, to showcase the remarkable potential of HTS technology. This fully functional prototype will undergo comprehensive cryogenic tests to validate the operational efficiency and stability of the all-HTS short period undulator under cryogenic conditions. It will also lay the ground for adoption by industry, as a blueprint demonstrating unique performance advantages, with the ultimate aim of capturing a segment of the market currently dominated by permanent magnets.

The characteristic parameters quoted are initial values, necessary to start the engineering design, and could be refined as the design progresses and upon input from the strategic roadmap (WP2), application studies (WP4), material and technologies (WP5), without however reducing the main demonstration objectives of the prototypes. Participation in the construction of the prototypes is also subject of industry co-innovation (WP3). Feedback from design, construction and, eventually, test will flow back into WP2, WP3 and WP4. Finally, it is our intention to use the prototypes beyond the scope of EuMAHTS, typically to produce background field for experiments and tests that require such advanced devices.

<u>WP9 – Test Infrastructures</u>. Test infrastructures and test methods are instrumental to the success of the work proposed. This work package ensures that existing EU test infrastructure is used at its best, by acting as a central point of coordination, and executing the necessary preparatory work to host materials and technology (WP5) and prototype (WP6, WP7, WP8) tests. Special accent is put on:

- Access to high field testing of REBCO HTS, to measure extensively not only the transport properties of HTS in field relevant to the planned development (ideally above 20 T), but also mechanical (delamination strength) and thermo-physical (solid and fluid heat transfer) characteristics;

- Access to variable cryogenic temperature installations, from liquid helium to liquid nitrogen temperature (4.2 K to 77 K), in a variety of cooling modes (gas convection, conduction in vacuum), to explore operation in different conditions of cryogenic heat transfer and cooling;

- Development and exploitation of novel sensors and measurement methods (e.g. for quench detection, dynamic field measurement, monitoring of temperature and strain) adapted to the unique challenges and new operating conditions of samples and coils produced within the scope of EuMAHTS.

Governance

The Governance, including the precise definition of all roles in the project, has been discussed among the participants and will be detailed, before the start of the project, in a Consortium Agreement Document that all participants will be required to sign. A sketch of the organization is shown in Fig. X3. This type of organization of the consortium is quite common in the communities of the various fields of activity participating in the proposal.

The Governing Board (GB) of EuMAHTS is the highest instance where all beneficiary partners are represented.

The Chair of the Governing Board is appointed by election among the representatives of the beneficiary partners. The Project Coordinator and Co-Coordinator report to the Governing Board on progress and issues, submit proposals for discussion and approval and receive recommendations for implementation. The Governing Board can call upon additional reports as it may see fit. The Chair of the Governing Board sits in the Technical Coordination Meeting, thus participating directly to the technical follow-up of the progress of EuMAHTS.

The Governing Board appoints an International Advisory Committee (IAC), whose role is to provide expertise, review and advice on technical progress and issues. The IAC reports directly to the GB, but all recommendations are shared with the PC and PCC.

Finally, it is the direct responsibility of the PC and PCC to ensure that the EU authorities are notified of milestones and deliverables, providing the planned high-quality reports. They also provide early notification in case of deviations, and propose suitable solutions. With the assistance and collaboration of the whole project structure, they act jointly for the success of the project.

Gender dimension and inclusiveness

EuMAHTS will not involve any research linked to the gender dimension. The promotion of gender balance is a constant preoccupation of the scientific communities involved in the project. It will hence be promoted at all levels, from the assignment of leading and research roles in the project, to hiring of the human resources such as students and post-docs financed by EuMAHTS. Concretely, the activities of the Gender and Inclusiveness Officer (GIO) in the project office will be devoted to promoting and monitoring gender equality and inclusiveness. The GIO will regularly report to the Collaboration Board and will be available to the Participating Institutes of EuMAHTS, staff and students, for advice and confidential contacts. The GIO will establish contact with social services of the participating Institutes, in particular at CERN, to address any issues arising in the project. The presence of family services inside the main hosting laboratories (housing, kindergarten, summer camps for children, recreation services) will provide all personnel with the same opportunities for travelling, will reduce the impact of family duties on careers and will improve the work/life balance. On the Dissemination and Outreach side, particular attention will be dedicated to events aiming to attract young women to STEM careers.

Open Science and Data Management

EuMAHTS brings together a diverse range of institutions and researchers who will produce research products of different complexity, sizes, formats serving different research communities and of course the public. Participating researchers are already practicing Open Science in their daily routine, and especially resorting on decades of Open Science experience in High-Energy Physics. CERN, a global leader in Open Science, is coordinating the consortium and has published in 2022 its institutional Open Science policy (OSP). The CERN’s OSP, collecting also input from other European institution, is the de-facto standard for Open Science in the field of High Energy and Accelerator Physics and will be taken as template for our policy.

EuMAHTS will build by M6 its Data Management Plan on CERN OSP, taking into account the diversity of the different participating Institutes, uniting the community to further its Open Science practices with the goal to maximize the impact of its research/project outputs.

As part of the proposal a thorough identification of expected outputs is already considered, e.g. data and public reports will be released with the appropriate open science and FAIR practices for those.

#§CON-MET-CM§# #§COM-PLE-CP§# #§REL-EVA-RE§#

2. Impact #@IMP-ACT-IA@#

EuMAHTS will develop and demonstrate disruptive magnet technology based on REBCO HTS. As we have made clear, this technology is far from being mature, especially at the level of fields, field gradients and stored energy targeted. Mastering the engineering challenges we have identified, successfully producing the three prototypes, and increasing the TRL, in collaboration with industry, will show that this magnet technology is ripe for wider diffusion and exploitation for scientific and societal applications.

HTS magnet technology has the potential for high performance at lower energy consumption and lower cost, enabling the expansion of the scientific scope of research infrastructures, facilitating the upgrade of existing research infrastructures and the design of new ones that would not be possible without this innovation.

Specific examples of the above are:

- Future colliders such as a full performance FCC-hh (100 TeV collision energy requires 18 T dipole magnets) or a Muon Collider (compact UHF solenoids with 40 T bore field to achieve small beam emittance are only possible using HTS).
- Light sources and free electron lasers whose spectrum and intensity will profit greatly from the technology developed by EuMAHTS, extending the analysis power well beyond present reach (quantify).
- High field user facilities for materials and life sciences, whose present performance is limited by power consumption, presently above 20 MW for a 30 T magnet. HTS magnets in the range of 30 to 40 T with negligible power consumption and simplified cryogenics will not only improve field reach and user availability at existing infrastructure, but also make new research possible at multiple sites.
- Fusion pre-industrial reactors, in tokamak technology but more specifically on stellerators, where currently on-going design specifications conduct to levels of compacity and coil topologies that may fundamentally benefit from the HTS developments.

In all the fields exposed above we expect that the expansion of these scientific-technological targets will influence on the expansion of the communities of users, attracting scientists of other regions to our research infrastructures.

Regarding translational aspects, we also expect positive impact in other fields of application, as soon as the technology finds first widespread uses, and experience is gained by operating the novel devices. Multiple fields may adopt HTS magnet technology once the initial risk is retired, such as MRI, energy production, energy storage or transportation.

We expect this project to impact on one more relevant aspect. The multidisciplinary of the applications of HTS facilitates a natural coordination within different scientific fields. EuMAHTS is very sensitive to contribute to the roadmaps of related communities. The major need of this technology creates a singular opportunity to enhance the coordination links among the accelerator, light sources and FELs and analytics communities, in a closer approach than on other technological aspects. We really expect this interaction to open a new frame of cooperation under balanced basis among our communities. The representation of partners of the three communities in EuMAHTS is a guarantee for such.

2.1 Project’s pathways towards impact

2.1.1 Immediate results

The main expected result of EuMAHTS is to advance HTS magnet technology, increasing its TRL from the present state of 3 to 4, to a target of 5 to 6. In system engineering this is generally done by identifying the performance drivers and limitations, and addressing them with technology development. EuMAHTS hosts such a development, in collaboration with industry. In this respect, EuMAHTS will also profit from the on-going work in a very dynamic field such as HTS R&D thanks to its multiple connections, through the several fields of application spanned, and the wide range of competence available in the Consortium.

In the case of EuMAHTS, in addition, the TRL advance will be fostered by the engineering and construction of prototypes, challenging physical realizations that will catalyse our efforts. The prototype magnets will also act as reality check and witness the level of TRL reached. Their in-field operation will demonstrate the state of readiness of the technology, and specifically whether HTS magnets are ripe for the next step of exploitation in research and industry. Specifically, we will test and monitor field reach, ramping time and field accuracy, magnet mechanical response and quench management, involving detection and protection strategy in different operating conditions. For all prototypes, whether designed for operation at liquid helium (for maximum performance) or higher temperature (for minimal consumption), we will test them at variable temperature, so to gather data and experience of operation in new cryogenic conditions.

We will obviously strive to meet the performance targets of the prototype, though we underline here that we mainly aim for a TRL increase, measured by how much the technology and technical solutions implemented are suitable for exploitation. But it is also important to underline that prototypes with satisfactory performance will become advanced test infrastructure for specific use, hosted by institutions that are beneficiaries of EuMAHTS. Specifically, the 40T-class solenoid could host materials testing, e.g. ultra-high-field critical current testing, so far not available in the EU at this level. The 10T/10MJ-class split solenoid is planned to be a test infrastructure for RF testing in field, as required by the R&D program of the Muon Collider study. And the K=2 undulator will see beams and will provide a proof of principle for an advanced beam line … (Marco, Sara to complement)

From the point of view of EU industry, the main result expected is an improved capability through the participation to co-innovation actions. We expect that better understanding of the issues, new engineering tools and direct experience will result in a reduced risk from the industry side, and correspondingly increased readiness to respond to follow up calls on HTS magnet projects. This will not only provide advantages to EU industry for EU projects, but also on a worldwide basis, where the field is evolving rapidly.

Finally, the strategic roadmap document will also be a direct and immediate result of the EuMAHTS work. Such a document does not yet exist, and we believe it will be highly beneficial to improve understanding and communication among fields of application, consolidate efforts, and optimize outcome of R&D for multiple fields. Indeed, we expect this document to provide crucial input to strategic initiatives such as the upcoming ESPP cycle.

2.1.2 Outcomes

Successful completion of EuMAHTS will generate very important outcomes. A proof of HTS magnet technology with the projected performance is most likely to convince research infrastructures to adopt it as baseline for upgrades, and to build future ones. Although further R&D and prototyping activities will be required to arrive to a specific implementation, such an outcome would not be possible, or would take longer without the contribution of the research planned within the scope of EuMAHTS.

A wider involvement of research and industry in future facilities based on HTS magnets will contribute to further reducing the risk of the technology, which is another outcome expected from the interest in the new technology elicited by EuMAHTS. And an element of risk reduction will be the exploitation experience of the first user facilities realized with HTS, first and foremost the EuMAHTS prototypes.

Further exploitation of the EuMAHTS results, building magnets for research infrastructures and other applications, will result in higher demand of HTS conductor for research applications. An increase volume procured and produced will send a tangible sign of interest for the specific field, it will facilitate discussion on specifications and required performance (beyond critical current), and will improving the response of industrial suppliers, in the EU and worldwide. Maintaining a strong link to superconductor industry is vital for HTS magnet technology, especially in a moment when industry is expecting pay-backs from the investments of the last years, mainly driven by fusion.

We also expect the strategic roadmap to yield beneficial outcomes. Such a roadmap will give strength to the field, it will provide the main institutional and industrial stakeholders with justification for support and investment, and will serve as good guideline to achieve best cross-field coordination, thus making most effective use of EU resources.

2.1.3 Long-term impact

The long-term impact that can be expected after the success of HTS magnet technology development and demonstration is that research infrastructures adopt it to reduce energy consumption, improve efficiency and sustainability at comparable or higher performance compared to the present state of the art. This is not only an ethically sound objective, but mandatory to move forward in the quest for discovery at the frontier of physics. To give an example, the projected electrical power required by a post-LHC hadron collider based on present technology (LTS) has been estimated at the level of 600 MW, for a consumption of xxx TWh per annum.

Reduction of this energy tag has evident priority.

A second long-term benefit of HTS magnet technology relying on cooling at high cryogenic temperature is to retire the risk of helium shortage. This risk is connected to that of the extraction and refinement of natural gas, and rather than a helium shortage, an inappropriate definition, concerns are for volatility of helium supply and price. A system that can be cooled with a minimal amount of cryogen, as could be engineered with dry-cooling, or that could even profit from alternative cryogens, would be obviously more robust against volatility than one based on a large inventory of liquid helium. To give again an order of magnitude, it has been estimated that the helium inventory for a post-LHC hadron collider based on present technology (LTS) would be in the range of 1000 tons, a rather high figure.

First exploitation of HTS magnet technology in user facilities would also increase acceptance, experience and induce a further risk reduction. This will induce wider interest in other fields of potential application, and likely adoption of this technology. One example that we can foresee are low and medium field MRI, operating in dry mode, that have no need of helium cooling, easier maintenance and deeper market penetration. Such machines could serve communities where access to maintenance means and qualified personnel is not easy, and improve healthcare on the long term.

The acceptance of HTS magnet technology, and multiple applications, will increase the demand of HTS conductor. The effect of an increased demand on HTS REBCO has been observed in the last five years, as the result of the procurement initiated by fusion start-ups that are developing compact tokamak machines. The performance of industrial REBCO has improved considerably, in particular at high cryogenic temperature in the range of 20 K, the production capacity has increased by an order of magnitude (multiple thousand km per year) and the production yield has increased. The result is that the cost of HTS REBCO has dropped to the point that it is now competitive with Nb_3Sn for high field applications when normalized to the unit length cost per unit current carried (kA m). The question is whether this remarkable result can be sustained over the next years. An increase of demand driven by sustainable needs, e.g. the MRI market, would provide much required stability to the supply chain. Also, it is expected that with steady sizeable production, standardization of demands and production methods, increased yield and automation, the cost of HTS REBCO conductor will drop further. This would consolidate REBCO as the high field superconductor of choice.

2.2 Measures to maximise impact - Dissemination, exploitation and communication #@COM-DIS-VIS-CDV@#

2.2.1 Scientific results

Scientific dissemination and communication activities will be the main instruments through which we plan to inform of the progress of EuMAHTS and attract the attention of research and industry. The Dissemination and Outreach Officer (DOO) working within the scope of WP1 will ensure that the plan is implemented effectively. The DOO will follow the dissemination and outreach plan based on the following concrete scientific actions, which are foreseen in the EuMAHTS budget to allow travel to conferences and workshops where the advances of HTS magnet technology may be presented:

- Organization of yearly community meeting for the whole project, expected duration of one week, with parallel sessions dedicated to each work package;
- Organization of topical workshops on cross-cutting and companion fields of science and societal applications
- Presentation of results to international conferences in magnet technology, applied superconductivity and cryogenics (MT, ASC, CEC, ICMC, ICEC);
- Participation to international conferences and workshops relevant to the fields of applications for which EuMAHTS is producing relevant advances;
- Scientific publications from each work package in international, peer reviewed journals, associated with milestone and delivery reports;

- Publication of a special issue on EuMAHTS, in an international journal of relevance in the field, towards the end of the project;

- Excerpts of specific progress and results will be advertised through the communication channels of the European Society for Applied Superconductivity (ESAS), the IEEE Council on SuperConductivity (IEEE-CSC) and the Cryogenic and Superconductivity Society of Japan (CSSJ). We will profit in particular from tbe services of the Superconductivity News Forum (SNF), providing a widely recognized early form of scientific publication in the field, whose editor will be a member of the research team (Prof. X. Obradors, ICMAB).

The scientific community, as well as the general public, will be informed through a dedicate project website, managed by a responsible for communication within EuMAHTS, in charge of preparing posts on social media. This activity will be in collaboration with the outreach services of CERN and other institutions. On top of scientific publications, a communication strategy will be established by the communication officer, to properly advert on the results through social media.

2.2.2 Strategy documents

HTS magnet technology is a crucial element of future research infrastructures such as large particle accelerators and high field user facilities. We will ensure dissemination of the results by delivering reports and participating to the strategy discussions of the respective fields. One such example is the European Stragey for Particle Physics, already quoted, due to take place during the duration of EuMAHTS. LIST OTHER OPPORTUNITIES ?

2.2.3 Management of research data and other outputs

The consortium will produce predominantly reports for internal and external use, as well as presentations in standard formats. As part of WP2, strategic roadmap, documents will be produced to be shared with the communities involved, higher strategic instances and the EU Authorities. WP3, industry co-innovation, will produce technical specifications of commercial nature, manufacturing drawings, industry design and test reports. WP4, applications design studies, and WP5, materials and technologies, will generate CAD and CAE models, as well as design and test reports. Finally, the prototype WP6, WP7 and WP8 will generate manufacturing drawings, design and test reports.

The expected size of these datasets is in the range of a few TB, and they will be made available as open data at CERN. We plan to use mainly the CERN Engineering Data Management System (EDMS), and connected databases, for all CAD drawings, CAE models, engineering and test reports. Reports of general interest and scientific publications will be stored in document repositories like the CERN Documentation Server (CDS) and Zenodo. Results will be made available to the whole consortium. Publications within the scope of EuMAHTS will follow the open access model. When relevant, results will be advertised to the general public using the social communication channels of the partners in the EuMAHTS consortium.

The EuMAHTS research and data outputs will follow the FAIR principles:

- <u>Findability</u> of research outputs: public reports will be published via established document repositories, such as the CDS, Zenodo and other institutional repositories of consortium partners if needed. Both CDS and Zenodo use persistent identifiers (DOIs) to identify the reports and are considered trusted repositories. Whenever possible, the research outputs will be linked e.g. to an article, further documentation, auxiliary measurements/datasets etc.

- <u>Accessibility</u> of research outputs: public reports and presentations will be made available through the repositories and the web sites. Detailed data and documents access provisions will be discussed as part of the Open Science Principles in the Data Management Plan.

- <u>Interoperability</u> of research outputs: the repositories currently identified for publishing the research outputs, use standardized metadata schemas (e.g. Datacite Metadata Standard) that enable easy discovery. Whenever possible and applicable, community standards will be used.

- Reusability of research outputs: the consortium will preserve its assets at CERN, by using the standard and trusted storage facilities and software tools already developed for the LHC machine and experiments. To further the reusability of research outputs, the consortium will aim at linking its research outputs to provide more context to the individual assets, e.g. designs, models, reports, articles are linked.

2.2.4 Communication with other communities

A strategic aim of EuMAHTS is an adequate coordination among accelerator, light sources and FELs and analytics communities. Regular meetings will be held with representing bodies of these communities to guarantee an efficient coordination among their respective roadmaps in what concerns HTS-based components and upgrades.

2.2.5 Communication with Industry

An efficient link with the industry is a pivotal need of EuMAHTS. This link will be implemented via fundamentally two ways: i) directly through the industry bodies of the accelerator, LEAPS and Fusion communities and ii) contacts via the national ILO offices.

#§COM-DIS-VIS-CDV§#

2.3 Summary

KEY ELEMENT OF THE IMPACT SECTION

SPECIFIC NEEDS	EXPECTED RESULTS	D & E & C MEASURES
What are the specific needs that triggered this project?	What do you expect to generate by the end of the project?	What dissemination, exploitation and communication measures will you apply to the results?
New magnet technology with higher field performance, significantly lower power consumption and cryogenic inventory at comparable or higher performance than present standard (LTS or resistive). Increased research capability for transdisciplinary European Research Infrastructures, including physics reach, lower energy consumption, increased sustainability, and wider exploitation possibilities. Examples of specific infrastructure: HEP (FCC-hh, Muon Collider) and NP (FAIR), LS (ESRF) and FEL (EUXFEL), HF (EMFL). EU industry participation to development, in preparation of the next step in magnet technology which is taking place, so to build upon its strong foundation and maintain a leading edge. An integrated strategic roadmap on HTS magnet R&D, integrating the needs of multiple research infrastructures and societal applications, to be delivered to institutional and industry stakeholders	Advance of HTS magnet technology, increasing its TRL from the present state of 3 to 4, to a target of 5 to 6. Prototype magnets, tested to demonstrate by in-field operation the state of readiness of the technology, and specifically whether HTS magnets are ripe for the next step of exploitation in research and industry. Prototypes with satisfactory performance will become advanced test infrastructure for specific use, hosted by institutions that are beneficiaries of EuMAHTS. EU industry will improve their capability through the innovation program, increase readiness to respond to follow up participation to HTS magnet projects, and decrease risk A strategic roadmap document, delivered to the EU as well as the ESPP and other comparable strategic initiatives.	The assessments and consolidated reports will be disseminated to the science community through scientific publication. Major results will be presented at international conferences. Workshops will be organised to promote dissemination, with sessions devoted to establishing connections and collaborations with companion programs, institutions and industry. Strategy documents will provide input for the ESPP process, as well as other comparable instances. Communication to the public will be achieved through the collaboration's website, social media, professional networks, and in liaison with other Accelerator EU programmes and societies such as ESAS, IEEE-CSC and CSSJ. CERN's and other Institutes' communication departments will be involved. Communication among different communities with research infrastructures benefitted from HTS will be a priority. An efficient link with the industry is a pivotal need of EuMAHTS, to include their capability in the HTS roadmap.

TARGET GROUPS

Who will use or further up-take the results of the project? Who will benefit from the results of the project?

Applied superconductivity and magnet communities for the various fields of application targeted, EU laboratories and universities.

EU industry involved in applied superconductivity and magnet technology.

European Research Infrastructures depending critically on magnet technology: CERN, FAIR, EUXFEL, ESRF, EMFL

Other fields of application where advances in magnet technology may provide significant progress: healthcare, energy, transportation

OUTCOMES

What change do you expect to see after successful dissemination and exploitation of project results to the target group(s)?

Research infrastructures will adopt HTS magnet technology as baseline for upgrades, and to build future ones, thus fostering R&D and prototyping activities beyond the results of EuMAHTS.

Wider involvement of research and industry will reduce the risk of the technology, also profiting from exploitation experience of first user facilities realized with HTS, including the EuMAHTS prototypes.

Higher demand of HTS conductor for research applications will facilitate discussion on specifications and required performance (beyond critical current), improving the response of industrial suppliers, in the EU and worldwide.

Strategies of research infrastructures of different fields will be aligned by providing the main institutional and industrial stakeholders with a clear shared roadmap, making most effective use of EU resources

IMPACTS

What are the expected wider scientific, economic and societal effects of the project contributing to the expected impacts outlined in the respective destination in the work programme?

Reduce energy consumption, improve efficiency and sustainability of research infrastructures at comparable or higher performance compared to the present state of the art.

Retire the risk of helium shortage, related to its connection to extraction and refinement of natural gas.

The risk reduction that will be brought by the experience of first user facilities will induce wider interest and adoption of this technology for other fields (e.g. medium field MRI without the need of helium cooling).

Multiple applications using HTS conductor will increase demand, improving the market, making it sustainable, large production capacity, and lower cost

#§IMP-ACT-IA§#

3. Quality and efficiency of the implementation #@QUA-LIT-QL@# #@WRK-PLA-WP@#

3.1 Work plan and resources

TO BE COMPLETED

Timeline of milestones and deliverables, critical decision points

Resources summary, M+P

Tables for section 3.1

Table 3.1a: List of work packages

Work package No	Work Package Title	Lead Participant No	Lead Participant Short Name	Person-Months	Start Month	End month
1	Coordination and Communication		CERN			
2	Strategic Roadmap		CERN			
3	Industry Co-innovation		CIEMAT			
4	Applications Design Studies		CEA			
5	Materials and Technologies		IFJPAN			
6	40T-class Solenoid		CERN			
7	10T/10MJ-class solenoids		INFN			
8	K=2 undulator		EUXFEL			
9	Test Infrastructures		CERN			

Table 3.1b: Work package description

Work package number	1
Work package title	Coordination and Communication

Objectives

Management of the project, coordination of work packages, administrative and documentary support, internal and external communication, dissemination and outreach, gender and inclusiveness considerations

Description of work

Participants to this work package are CEA, CERN (coordinator), CIEMAT, INFN, PSI and UMIL. This work package consists of four tasks:

- T1.1 - Oversight and Management, which includes all activities to run EuMAHTS as a project. The Project Coordinator (PC) and Project Co-Coordinator (PCC) call and chair project meetings, receive reports from the work packages, follow-up on progress and resolve issues, reporting to the Governing Board and the EU Authorities. This task is led by CERN, with the participation of CEA and UMIL
- T1.2 - Project Coordination and Administrative Support, providing the required resources and means to follow-up on milestones and deliverables, preparing and submitting reports to the EU, organizing meetings, reviews and events, in particular the EuMAHTS annual meetings and topical workshops. The Project Management Officer (PMO) and the Administrative and Documentary support Officer (ADO) manage the project processes, monitor milestones and deliverables, control budget, provide engineering data management and document storage in accordance with the FAIR standards. This task is led by CERN, with thew participation of INFN
- T1.3 - Diversity and Inclusiveness, following up on the gender dimension and ensuring that an inclusive policy is implemented throughout the project. The Gender and Inclusiveness Officer (GIO) provides policy and support to project participants in all above matters, and reports on any related issues and follow-up. It is planned to have specific diversity and inclusiveness topics included in the EuMAHTS annual meetings. This task is led by INFN, with the participation of CIEMAT.
- T1.4 - Communication, Dissemination and Outreach activities, in charge of providing wide resonance to the needs and results of the project. The Dissemination and Outreach Officer (DOO) prepares such communication actions, liaising with the communication and outreach offices of the participants. It is planned to organize two outreach events in concomitance with the EuMAHTS annual meeting for years 3 and 4. This task is led by INFN, with the participation of PSI.

WP1 is in charge of calling the monthly meetings of the EuMAHTS Project Office (PO), and the bi-monthly meetings of the EuMAHTS Technical Coordination Meeting (TCM).

Work package number	2
Work package title	Strategic Roadmap

Objectives

Explore synergies among multiple fields of research and applications of HTS magnet technology, with the aim of elaborating a shared Global HTS Roadmap. This document will propose concrete actions and a plan for maximizing the impact of HTS on science and society.

Description of work

Participants to this work package are CEA, CERN (coordinator), LNCMI, TERA-CARE, EMFL, ESRF, EUXFEL, GSI, HFML, HLD, PSI, UMIL. This work package consists of three tasks:

- T2.1 - Coordination, directing technical tasks T2.2 and T2.3. WP2 will establish a list of contacts in all relevant communities and bodies that should participate to the work. This task will take care of organizing internal meetings, facilitating communication and exchange of information among the various fields of applications, making documentation available and organizing general meetings and workshops with wide participation from the EU and beyond.

- T2.2 Roadmaps Analysis and Discussion, covering the collection and review of the relevant documentation from previous EU funded programs on HTS as well as roadmaps and action plans of the various fields of activity mentioned in this proposal. As applicable, WP2 will propose means to merge HTS activities in the different disciplines, with the goal of improving synergies and impact of HTS in each field, homogenise the approach, mutualize infrastructure and R&D lines. The main outcome of this task will be a white paper to be discussed in a General HTS Strategy meeting (T2.3).

- T2.3 Global HTS Roadmap for Science and Society, built upon the effort of Task 2.2, with primary scope to provide for the first time a Global HTS roadmap, where the development of HTS is pursued in a coherent way across all fields. The objective is to maximize affordability, sustainability and innovation in European Research Infrastructure and provide a maximum input for scientific and societal applications.

WP2 will initiate and maintain the EuMAHTS Strategy Forum, supporting the consultation and synthesis activities of T2.2 and T2.3. In the last year of activities, WP2 will act to promote acceptance of the Global HTS roadmap, e.g. participating to strategic meetings and lobbying with governance bodies, and organize a joint event with WP3 to inform and facilitate market penetration of HTS magnet technology for green energy and healthcare.

Work package number	3
Work package title	Industry Co-innovation

Objectives

The objective of this work package is to engage European Industry in a co-innovation program with development actions directly related to HTS magnet technology, and to strengthen the link between European HTS research and industry.

Description of work

Participants to this work package are CIEMAT (coordinator), CEA (co-coordinator), CERN, ESRF, EUXFEL, GSI, ICMAB, INFN and PSI. This work package consists of two tasks:

- <u>T3.1 - Coordination</u>, directing technical tasks T3.2 and T3.3.
- <u>T3.2 - Co-innovation Program</u>, which includes the selection of co-innovation actions among those defined at the time of the proposal, or other proposed by the participants, opening the calls, placing PCP contracts with EU industry, and following up progress, ensuring that the results are exploited to the maximum possible within the scope of EuMAHTS. The mechanisms of selection, advertisement and adjudication and project follow-up are described in the main body of the proposal, and will be part of the Consortium agreement. This task is led by CIEMAT, with the participation of CEA, CERN, ESRF, GSI, ICMAB, INFN and PSI.
- <u>T3.3 - Coordination with Industry</u>, aiming at forming a reliable and stable connection between European research and industry in HTS. This task will create a board with focus on HTS, as a permanent forum that will maintain its activities after the conclusion of EuMAHTS. To ensure efficient work, the activity will be coordinated with the recently created Accelerator Industry Permanent Forum (AIPF) and the industry board of the League of European Accelerator-based Photon Sources (LEAPS), as well as other existing boards and associations such as Conectus.

This work package hosts the activity of the Internal Selection Committee (ISC) composed of a representative of each of the participants to this work package and one member of the Project Office appointed by the Project Coordinator. The ISC will be chaired by the WP3 Coordinator. The main task of the ISC will be to select co-innovation actions among the set proposed, based on the criteria detailed in the body of this proposal.

We plan to implement at least three-four co-innovation actions, or more if fits within the budget, depending on the selection and industry response.

Work package number	4
Work package title	HTS Magnets Applications Design Studies

Objectives

Explore the potential and challenges of HTS magnets through the establishment of performance targets, studying innovative design concepts, identifying key issues and R&D needs, and quantifying potential impact on the multiple fields of application considered. Focus of the studies is on performance, energy efficiency and sustainability.

Description of work

Participants to this work package are CEA (coordinator), CERN, ESRF, EUXFEL, GSI, ICMAB, INFN, PSI, TAU, TERA-CARE. This work package consists of 6 tasks. Given the broad spectrum of WP4, the work has specific sub-objectives, as described below:

- <u>T4.1 - Coordination</u>, ensuring appropriate coordination, collaboration and knowledge sharing among the various tasks in WP4, , as well as liaising with other WP's. Beyond the day-to-day management of the work package, this task will focus on fostering communication and alignment across all activities. To achieve this, a series of workshops will be organized on applications of HTS magnets. These workshops will feature dedicated sessions for each task, such as a session on "Energy & Sustainability for HTS Applications" or a user meeting with MRI industry manufacturers.

- T4.2 - Energy efficiency and sustainability, Evaluate the sustainability of a wide range of application of HTS devices applications for scientific and societal purposes. Identify various applications, providing input and consultancy to WP6, WP7, and WP8. The task focuses on a specific case study of loss, cooling, and energy efficiency for an HTS beam transfer magnet (initial proposal), developing a model for sustainability assessments, and proposing a Figure of Merit (FoM). Collaborating with various work packages, it covers scientific applications like nuclear facilities, high-energy physics setups, and medical infrastructure, particularly synchrotrons and gantry systems for heavy-particle therapy. Following the analysis, guidelines and FoMs will be established and shared with relevant work packages, with stakeholder engagement facilitated through participation to workshops, and outcomes disseminated through outreach activities.

- T4.3 - High Energy Physics and Nuclear Physics Applications, starting with an analysis the state of the art of the accelerator magnets, pointing out the performance limits of the LTS magnets currently used and extrapolating realistic performances that can be achieved by using HTS superconductors. The use of HTS technology would enable achieving much higher fields, ideally 20 T for dipoles and 40 T for solenoids, outperforming existing LTS conductors, e.g. Nb-Ti in LHC (8T) and Nb_3Sn in HL LHC (12 T) and operate at cryogenic temperature around 20 K. This would improve the sustainability of accelerator facilities and be a real game changer in nuclear and high energy physics. A feasibility study of an HTS accelerator dipole will be performed, addressing the following challenges: (i) Analysis of the status of the art of the conductor and identification of the priorities of its R&D; (ii) Study of quench protection systems suitable for insulated or non-insulated (from 0 to finite value of inter turn resistance) cables; (iii) Development of novel mechanical support structure to address the anisotropic properties of HTS conductors; (iv) Optimization of the magnet thermal design optimizing the HTS conductor to work at temperatures above liquid helium with indirect cooling or forced gas cooling solutions.

- T4.4 - Applications for Analytical Research Infrastructures, assessing the potential of HTS magnet technologies in enhancing light and neutron sources, as well as supporting high magnetic field facilities for analytical research infrastructures. Achievable field strengths and gradients for HTS undulators and quadrupoles will be determined, aiming at brighter, more coherent and tunable beams in light sources, while exploring new possibilities for neutron scattering systems and higher magnetic field magnets. Extensive design and simulation studies will be carried out to assess the feasibility of short period high field undulators (> 1000 T/m), *super-bend* magnets, higher order multipolar small aperture magnets for light sources and free electron laser (FEL) applications. Specific studies will be carried out to identify the benefits and challenges of using HTS to improve the performance of neutron scattering magnets and to explore higher magnetic fields beyond 50T.

- T4.5 - Medical applications, assessing the state of the art and the potential of HTS magnet technologies in medical applications by identifying benefits and challenges and providing a detailed analysis for at least one application. The task involves identifying and describing specific applications for each subtask, such as compact synchrotrons and rotating gantries for ion therapy, cyclotrons with steady-state large bore magnets, and MRI machines with ultra-high field capabilities. It also includes assessing the state of the art in these applications, defining threshold values for HTS components, identifying gains and challenges for each application, organizing a user meeting with MRI industrial manufacturers to address obstacles and potential benefits of transitioning to HTS technology, and providing input to WP5 while conducting a detailed analysis for at least one application.

- T4.6 - Energy and Transportation, Exploring diverse, high-impact applications of HTS magnet technologies in energy and transportation. Study diverse, high-impact applications of HTS technologies in areas such as fusion reactors, electrical machines, transportation and levitation systems. By exploring state-of-the-art limits and defining "game-changing" performance thresholds for each application (magnetic field, temperature, force, power, cost), the task will systematically evaluate viable conductor options and magnet configurations (choice of tape, conductor, geometry, cooling) to unlock the full potential of HTS in these fields.

The findings of WP4 will be shared through participation to workshops and meetings, and discussed within EuMAHTS to guide the development of prototypes (WP6, WP7, WP8).

Work package number	5
Work package title	Materials and Technologies

Objectives

Support studies and prototype construction and test through targeted R&D on materials, components and manufacturing solutions

Description of work

Participants to this work package are CERN, CUT, EUXFEL, IJPAN (coordinator), INFN, KIT, PSI, TAU, UTWENTE. This work package consists of 7 tasks:

- T5.1 – Coordination, ensuring appropriate coordination, collaboration and knowledge sharing among the various tasks in WP5, as well as liaising with other WP's.
- T5.2 - Energy efficient and sustainable cryogenics, TO BE COMPLETED
- T5.3 - HTS conductors and cables, TO BE COMPLETED
- T5.4 - 3D coils winding, mechanics and tooling, TO BE COMPLETED
- T5.5 - HTS quench management and insulation control, TO BE COMPLETED
- T5.6 - Radiation properties and radiation hardness, TO BE COMPLETED
- T5.7 - Joints and terminations, TO BE COMPLETED

Work package number	6
Work package title	40T-class all-HTS solenoid

Objectives

Development, fabrication, and test of an all-HTS ultra-high field solenoid (40T-class) prototype with 50 mm clear bore.

Description of work

Participants to this work package are CEA, CERN (coordinator), IFJPAN, INFN, PSI, UMIL, UNIGE, UTWENTE. This work package consists of four tasks:

- T6.1 - Coordination, overseeing the integration and coordination of the tasks. This task will also manage the procurement of superconductors, a critical component for the project's success. This task is led by CERN
- T6.2 - Engineering design, encompasses a comprehensive suite of activities including
  - Electro-magnetic and Mechanical Design: Crafting a design that integrates magnetic and mechanical requirements to ensure structural integrity and performance.
  - Thermal Design: Developing thermal management strategies to maintain optimal operating temperatures and ensure stability.
  - Quench Detection Studies: Investigating methodologies for identifying abrupt losses in superconductivity, critical for maintaining magnet integrity.
  - Magnet Protection Studies: Assessing and implementing measures to protect the magnet from potential damages during operation or quench events.
  - Design of Quench Detection and Protection Systems: Engineering systems to detect quenches and protect the magnet, ensuring reliability and safety.
- T6.3 - Prototype fabrication, build a prototype that includes design features and technology suitable to reach the target field of 40 T in a clear bore of 50 mm. This phase involves several key activities, in collaboration with WP4 and WP5, synchronizing efforts on material studies and the development of technologies:
  - Fabrication Studies and Design for Manufacturing: Conducting studies to refine the fabrication process and adapting the design to facilitate manufacturing.
  - Component Fabrication and Assembly: Sourcing materials, fabricating or procuring components, and assembling solenoids.
  - Manufacturing of Sub-Scaled Pancakes and Solenoids: Creating 20T-class prototypes as intermediate steps towards the final 40T-class prototype.
  - Production of the 40-T class prototype: Realizing the full-scale prototype to meet the project's magnetic field goal.
- T6.4 - Experimental Assessment, involving a thorough evaluation of the technologies employed in the 40T-class prototype through a series of tests, planning and coordinating with WP5 and WP9 to ensure access to the appropriate test infrastructures for assessing the superconducting properties of the conductors and the performance of the manufactured magnets:
  - Testing of Electrical Joints: Evaluating the performance and reliability of electrical connections within the 40T-class prototype.
  - Measurement of Transversal Electrical Resistance: Assessing the electrical resistance in soldered conductor stacks, representative of the conductor winding in the 40T-class prototype.
  - Testing of sub-scaled prototypes: Conducting tests on sub-scaled prototypes at temperatures ranging from 4.2 K to 77 K to validate the technologies intended the 40T-class prototype.
  - Final Testing of the 40T-class Prototype: Verifying the prototype's capability to achieve the target magnetic field strength, marking the culmination of the experimental assessment.

Work package number	7
Work package title	10T/10MJ-class All-HTS Solenoid

Objectives

Development, fabrication, and test of an all-HTS split field and large stored energy solenoid (10T/10MJ-class) prototype with 300 mm clear bore and significant split pair aperture, approximately 200 mm, to provide room temperature access.

Description of work

Participants to this work package are CERN, CIEMAT, INFN, UMIL (coordinator). This work package consists of four tasks:

- T7.1 - Coordination, overseeing the integration and coordination of the tasks. This task will produce the master schedule of the prototype, follow progress of internal milestones and produce the deliverables, implement a suitable Quality Plan, shared with WP1, WP6 and WP8. This task will maintain the strong collaboration with other WPs to promote industrial participation (WP3), receive input and provide feedback to studies (WP4) and technologies (WP5), and share results with the other prototypes (WP6, WP8). This task is led by UMIL.
- T7.2 - Design and analysis, focusing on the engineering design of the split solenoid. It starts by carefully assessing the state of the art of HTS magnet R&D both in EuMAHTS partners and outside the project, including other European and extra-European institutes and research groups. As a result, candidate technologies are identified to feed the prototype conceptual design. This phase will cover magnetic aspects, to identify a preliminary magnetic layout for the device, followed by integration with preliminary mechanical design, including the support of split forces, cooling scheme, and protection scheme. Cable splicing technology, (non-)insulation technology, cryogen-free cooling, and quench protection scheme will be selected based on technology samples and measurements. The design and experimental efforts will converge in the engineering design, documented in a Technical Design Report (TDR) that includes manufacturing drawing and contains the BoM (bill of material). The TDR will provide all necessary input and information to start procurement, manufacture parts and coils, and assemble the split solenoid.
- T7.3 - Prototype fabrication, covering the complete procurement and manufacturing of the split solenoid prototype. Based on the TDR produced in T7.2, this task includes procurement of materials and components, preparation of sub-scale, mock-up and samples, fabrication of final parts and coils, and final assembly. Manufacturing will take place following the successful assessment of manufacturing readiness. Participation of industry in this task is a possibility foreseen in WP3. This task is concluded with a fabrication report.
- T7.4 - Prototype testing, responsible for performing all the necessary experimental activities on the sub-scale and prototype, including the preparation of a test program to be carried out for acceptance and performance evaluation. The scope of this task covers the design and procurement of the measurement systems (sensors, hardware) specific to the operation, protection and diagnostic of the prototype to be tested. The task will provide support to integration of these instruments in the prototype. Finally, the task contributes to operation of the test stations, perform measurements and process results, in close coordination with WP9 and the relative test infrastructures, ensuring best use of available resources, personnel and facilities.

Work package number	8
Work package title	K=2 All-HTS Undulator

Objectives

Develop, fabricate, and test an all-high-temperature superconductor (HTS) short period undulator. The primary goal is to demonstrate the superior magnetic field performance of HTS compared to the widely used

NbTi, a prevalent low-temperature superconductor in current industrial applications.

Description of work

Participants to this work package are ESRF, EUXFEL (coordinator), IFJPAN, PSI. This work package consists of four tasks:

- T8.1 - Design and analysis of the prototype. Develop the magnetic design, incorporating effective quench protection measures to ensure the reliability and safety of the all-HTS short period undulator.
- T8.2 – Manufacturing solutions, implement comprehensive procedures for joints, winding, and impregnation (or soldering) on planar undulator coils, drawing inspiration from existing practices for NbTi coils. Manufacture small prototypes with diverse designs and geometries to validate numerical models and explore insulated, partially insulated, and non-insulated coil configurations.
- T8.3 - Prototype construction, procure necessary HTS materials and yokes for the undulator construction, ensuring compatibility and adherence to project specifications. Execute the coil manufacturing process, including winding, impregnation, and assembly, following established procedures to achieve high-quality undulator components.
- T8.4 - Prototype test, prepare for cryogenic tests at the SUNDAE1 test stand under construction at EUXFEL by setting up instrumentation for magnetic measurements, including a Hall probe sledge for estimating the magnetic profile, K-value, and magnetic field quality. Incorporate temperature sensors and quench protection mechanisms. Coordinate efforts with Task 9.3 for synergies in the cryogenic test setup. Conduct tests.

Work package number	9
Work package title	Test Infrastructures

Objectives

Exploit existing EU test infrastructure for high field testing in variable cryogenic temperature environment with extended and novel measurements capability for the characterization of novel materials, technologies and demonstrators.

Description of work

Participants to this work package are CERN (coordinator), ESRF, EUXFEL, IFJPAN, INFN, UMIL, UNIGE. The work is in support of operation and extension of the available test capacities for HTS. Specifically, the task includes:

- Testing of HTS conductor at background field at the variable cryogenic temperatures and with variable field angles, to provide data on tape samples for use in the other work packages;
- Testing of small HTS test solenoids as stand-alone or inside a background field;
- Ensuring test capacity for the prototype magnets for WP6 (40T-class solenoid), WP7 (10T/10MJ-class split solenoid) and WP8 (K=2 undulator);
- Ensuring that instrumentation and diagnostics tools are up to date for quench detection and quench protection;
- Contributing data reduction and performing analysis of conductor performance, quench localization, and magnetic field mapping.

This work package consists of four tasks:

- T9.1 – Coordination, to create and maintain up to date a list of test stations and their test capabilities within the collaboration. Include instrumentation capacities. Work in synergy with the existing network on superconducting magnet test, for example through the regular workshop on “Superconducting Magnet test facilities’ and “Instrumentation and Diagnostics for Superconducting Magnets”. Collect the requirements and test station specifications from work packages 5, 6, 7 and 8. Include cryostat geometry, cryogenic conditions. Ensure synergy for the quench detection and protection, which is a critical for testing HTS magnets.
- T9.2 - Conductor characterization, characterize batches of conductor, in support of WP5 to WP8, while testing in background field, including field angle dependency and variable temperatures.
- T9.3 - Models and prototype testing, identify test facility and upgrades for demonstrator testing of the 40 T solenoid, the split coil solenoid and the undulator.
- T9.4 - Diagnostics, Instrumentation and Measurements, identify needs and implementation of diagnostics, instrumentation and measurements for the testing of models, prototypes and demonstrators, including quench detection, magnetic measurements, performance diagnostics, etc.

Table 3.1c: List of Deliverables

Number	Deliverable name	Short description	Work package number	Short name of lead participant	Type	Dissemination level	Delivery date (in months)
D1.1	Final report of EuMAHTS	Main results of the project, exploitation and perspective	1	CERN	R	P	46
D3.1	R&D industry action selection	Report on the action selection and tendering processes.	3	CIEMAT	R	P	18
D3.2	R&D industry program	Report on the R&D industry program development and	3	CIEMAT	R	P	46

		analysis of its impact					
D3.3	Industry coordination	Report on the impact of the coordination actions with the industry	3	CERN	R	P	44
D2.1	Global HTS Roadmap	Roadmap for the optimal and fastest implementation of HTS in all communities and for societal applications	2	CERN	R	P	36
D6.1	40 T Solenoid Test Report	Main results obtained from the test of a 40 T solenoid prototype	6	CERN	R	P	44
D4.1	HTS Magnet Applications Interim Report	Interim report on HTS Magnet Applications.	WP4	CEA	R	P	18
D4.2	HTS Magnet Applications Final Report	Final Report on HTS Magnet Applications.	WP4	CEA	R	P	36
D7.1	Conceptual Design Report	Report with complete list of parameters motivating the choice for the design, covering magnetic, electrical, protection, thermal and mechanical aspects	7	INFN	R	P	8
D7.2	Technical Design Report	Report with the complete final design, supported by experimental results carried in the EU-MAHTS framework	7	UMIL	R	P	20
D7.3	Manufacturing Report	Final SCD magnet fabrication report	7	INFN	R	P	38
D7.4	Testing Report	Report with coil test results	7	UMIL	R	P	46
D8.1	Magnetic design	Magnetic design	8		R	P	24
D8.2	Quench protection scheme	Quench protection scheme	8		R	P	36
D8.3	Completion coils manufacturing	Completion coils manufacturing	8		R	P	40
D8.4	Results tests	Results tests	8		R	P	48
D8.5	Analysis and lessons learned	Analysis and lessons learned	8		R	P	48
1	D1	Characterization of	9	UNIGE	R	P	48

		superconducting properties of HTS tapes in background field with variable field angle and variable temperature					
2	D2	Test infrastructure readiness for test of model and prototype magnets for work packages 6, 7 and 8	9	CERN	R	P	48

Table 3.1d: List of milestones

Milestone number	Milestone name	Related work package(s)	Due date (in month)	Means of verification
M1.2	Project kick-off meeting	1 + 2,3,4,5,6,7,8,9	3	Meeting indico site
M1.1	Data management plan	1	6	Report
M1.3	First annual meeting	1 + 2,3,4,5,6,7,8,9	14	Meeting indico site
M1.4	Second annual meeting	1 + 2,3,4,5,6,7,8,9	26	Meeting indico site
M1.4	Third annual meeting	1 + 2,3,4,5,6,7,8,9	38	Meeting indico site
M1.5	Project closing meeting	1 + 2,3,4,5,6,7,8,9	46	Meeting indico site
M3.1	Selection of the co-innovation actions	3 + 1	4	Report
M3.2	Market consultation	3 + 1	7	Report
M3.3	Review of the situation of the contracts for the selected R&D industrial actions	3 + 1	18	Report
M3.4	Analysis of applicability to WP6-8	3 + 1	20	Report
M3.5	HTS Industry Network	3 + 1	12	Report
M3.6	Summit industry – Research Institutions	3 + 1	44	Report
M2.1	Strategy kickoff *Kick-off meeting with the widest EU and non-EU contact person for HTS in each community*	2 + 1,3	6	Report
M2.2	HTS-broad picture *summary of all on-going HTS programs, as well as budget and personnel, across all communities*	2 + 1,3	12	Report
M2.3	HTS Strategy Workshop *Discussing HTS implementation across all communities*	2 + 1,3	24	Report
M2.4	Workshop for societal application; *the workshop will include Academia and Industry*	2 + 1,3	34	Report
M6.1	Engineering Design	6 + 1,3	24	Fabrication Drawings and report
M6.2	Prototype Fabrication	6 + 1,3	42	Manufacturing drawings and report
M6.3	40 T Test Station	6 + 1,3,9	36	Review 40 T test station
M4.1	HTS Magnet Technology Information Workshop	4	12	Meeting indico site
M4.2	HTS Magnet Technology	4	36	Meeting indico site

	Final Workshop			
M7.1	Conceptual Magnetic Design	7	5	Report
M7.2	Technical Magnetic Design	7 + 5	16	Report
M7.3	Manufacturing Readiness	7 + 1,5	28	Report
M7.4	Coils Manufacturing	7 +5,9	34	Report
M8.1	Magnetic design	8 + 5	24	Report and review
M8.2	quench protection scheme	8 + 5	36	
M8.3	Purchase HTS and yoke for the prototype	8 + 1,3	18	Purchase orders
M8.4	Completion coils manufacturing	8	40	Report with pictures and electrical measurements
M8.5	Test of the prototype	8 + 9	48	Report of measurements
M8.6	Analysis and lessons learned		48	Report and review
M9.1	Identification and inventory of existing infrastructure and needs for EU-MAHTS	9	12	Report
M9.2	Characterization of first batch of HTS tape with variable field angle	9 + 5,6,7,8	18	Report with test results
M9.3	Test station ready for first test of solenoid model coil	9 + 6,7	24	Test station commissioning report
M9.4	Test station ready for first test of full prototype	9 + 6,7	36	Test station commissioning report
M9.5	Quench protection study and proposal	9 + 4,5,6,7,8	30	Report and hardware

Table 3.1e: Critical risks for implementation #@RSK-MGT-RM@#

Description of risk (indicate level of (i) likelihood, and (ii) severity: Low/Medium/High)	**Work package(s) involved**	**Proposed risk-mitigation measures**

#§RSK-MGT-RM§#

Table 3.1f: Summary of staff effort

	WPn	**WPn+1**	**WPn+2**	**Total Person-Months per Participant**
Participant Number/Short Name				
Participant Number/ Short Name				
Participant Number/ Short Name				
Total Person Months				

Table 3.1g: 'Subcontracting costs' items

Participant Number/Short Name		
	Cost (€)	Description of tasks and justification
Subcontracting		

Table 3.1h: 'Purchase costs' items (travel and subsistence, equipment and other goods, works and services)

Participant Number/Short Name		
	Cost (€)	Justification
Travel and subsistence		
Equipment		
Other goods, works and services		
Remaining purchase costs (<15% of pers. Costs)		
Total		

Table 3.1i: 'Other costs categories' items (e.g. internally invoiced goods and services)

Participant Number/Short Name		
	Cost (€)	Justification
Internally invoiced goods and services		
…		

Table 3.1j: 'In-kind contributions' provided by third parties

Participant Number/Short Name			
Third party name	Category	Cost (€)	Justification
	Select between Seconded personnel Travel and subsistence Equipment Other goods, works and services Internally invoiced goods and services		

#§QUA-LIT-QL§# #§WRK-PLA-WP§#

3.2 Capacity of participants and consortium as a whole #@CON-SOR-CS@# #@PRJ-MGT-PM@#

The consortium comprises XX Institutes out of which X1 are Beneficiaries and X2 Associates. The idea to setup a

European Project to develop HTS magnet technology has already attracted much attention and reached the goal of uniting the interests of several fields of science. Accordingly, the Consortium will comprise leading Laboratories and Universities from the following fields:

- High Energy Physics and Nuclear Physics
- Light Sources and Free Electron Lasers
- High Field User Facilities for materials and life sciences
- Energy
- Medical applications

Indeed, we count among the beneficiaries five research infrastructures of Europen interest: CERN, hosting the High Luminosity LHC (HL-LHC), GSI, hosting the Facility for Antiproton and Ion Research (FAIR), The European X-ray Free Electron Laser (EUXFEL), the European Synchrotron Radiation Facility (ESRF) and the European Magnetic Field Laboratory (EMFL).

CERN will coordinate the project, profiting from its experience leading the R&D efforts in accelerator physics and technology at European level. CERN participates with in-kind resources in almost all work packages, and will serve as a host for project management, administrative and documentary support, hosting consortium meetings and events. CERN has a long experience in managing complex European studies such as EuCARD, EuCARD2, ARIES, and the on-going iFAST, and has developed over the years tools for collaborative work that will be put at the disposal of the consortium.

Besides the quoted Research Infrastructure hosts, the Consortium includes a balanced mix of Laboratories and Universities, most of them with established competence in superconducting magnets and associated technology. Several members of the Consortium have a multi-disciplinary mission (e.g. laboratories such as CEA, CIEMAT, KIT, and universities such as TAU, UMIL, UTWENTE, UNIGE), which is indeed appropriate given that EuMAHTS intends to build bridges among communities straddling several fields of application of HTS magnet technology. This is also beneficial to ensure that all EuMAHTS participants remain fully aware of progress and opportunities across several fields, thanks to the existing network of each participant, shared within the scope of EuMAHTS.

Along these lines, we draw the attention to the fact that the EUROFusion Consortium will take part to the activities of WP2 package. We believe that in the present Although EUROFusion is not a Legal Entity, leading EUROFusion associates have recently signed an agreement with CERN for a collaboration in matters of science and technology of relevance to fusion and high energy physics. The participation of EUROFusion to EuMAHTS WP2 will be regulated by a specific addendum which has been drafted and will be signed as soon as the Consortium agreement is completed.

We recognize the importance of universities in the Consortium, to ensure the link to academia, attracting young generation of researchers, and providing appropriate scientific support to the studies in EuMAHTS, but also a platform to hire the required PhD students and PostDocs. This is why the Consortium includes universities with recognized standing in HTS materials and magnet technology.

The Consortium mechanism is also well proven, based on template and previous experience at CERN. Each participant has provided a letter of commitment for the resources quoted in this proposal, should EuMAHTS receive the requested EU funding. This will be an integral part of the Consortium agreement, which will provide the formal means to govern the project, as we detailed earlier. In fact, the Consortium has sufficient overlap of competencies, especially in the participants with large capacity. This ensures that all work packages can be executed, even in the unlikely case that one of the participants should withdraw.

Finally, participation of European industry is an integral part of the research program. We have a clear scope, and well-defined mechanism by which industry will participate to the innovation process driven by EuMAHTS (see WP3). The technical risk reduction implied by the co-innovation scheme proposed is very likely to attract attention from multiple industrial actors, those already established as well as new-entries. We hence expect that a healthy combination of competition and risk-reduced development will foster European industry participation.

In summary, a consortium of such broad band, resting on the very solid base of five Research Infrastructure of European interest, including engagement of European industry, and governed by a mechanism well proven by the success of previous similar projects, guarantees a qualified and resilient organization. But, beyond the project execution, we also expect to provide unprecedented opportunities for exchange of know-how across fields and communities, leveraging on multiple competences in the Consortium, and thus initiate a major, EU-wide technology advance, profiting science and society at large.

#§CON-SOR-CS§# #§PRJ-MGT-PM§#