Proposal template Part B: technical description

EuMAHTS

Magnet technology Advances for European research infrastructures through HTS

[This document is tagged. Do not delete the tags; they are needed for processing.] #@APP-FORM-HERIAIA@#

List of participants

Participant No. *	**Participant organisation name**	**Country**
1 (Coordinator)	CERN	
	CEA	
	EMFL	
	ESRF	
	EUXFEL	
	GSI	
	IFJPAN	
	INFN	
	KIT	
	PSI	
	TERA-CARE	
	TAU	
	UMIL	
	UTWENTE	
	UNIGE	
	UUPPSALA (?)	

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 multiple fields of scientific and societal application. We target in particular High Energy Physics, Nuclear Physics, Materials and Life Sciences, Medical and Energy applications.

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, i.e. 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.

Achieving such substantial increase of TRL requires a strong connection with European industry, who will take active part thanks to the co-innovation initiative included in the scope of EuMAHTS.

In fact, the prototype magnets proposed are not only technology challenges, they are directly inspired and represent the next step in magnet technology for many fields of science and societal application. A direct involvement of industry in EuMAHTS will hence prepare European industry response to upcoming requests for such magnets, as well as facilitate market penetration of HTS magnet technology in a near future.

1.1.1 Background

Nearly forty years after their discovery [1986-BED], High-Temperature Superconductors (HTS) appear to be 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], the development of high field magnets for compact fusion reactors that could accelerate the energy transition [2021-MIT], which has driven large investment at manufacturing sites resulting in cost reduction [2021-MOL], and, last not least, heightened awareness on the importance of energy efficiency and sustainability.

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 is not only possible reducing helium inventory, but 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 environmentally friendly systems, improve sustainability, and achieve profitable economics over the long term.

Several fields of scientific and societal applications could profit from the above properties of HTS materials. 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 [NEUTRONS];

- Healthcare and Life Sciences: HTS magnets are expected to further enhance analysis devices like NMR (Nuclear Magnetic Resonance) [NMR] and medical imaging devices like MRI (Magnetic Resonance Imaging) [RADBOUD], 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. It is also likely that 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 Transmission: HTS materials may improve the efficiency and performance of electrical generators and power transmission systems, enhancing the overall stability and reliability of the electrical grid. 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.

The declared scope of EuMAHTS encompasses HTS magnets, we will not address the electrical engineering challenges of power conversion and transmission. But EuMAHTS encompasses 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.

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 the push towards high magnetic fields for materials and life science has the this evolution 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]. 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 [NI Patent]. 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) [45.5T] and 32.5 T at LNCMI also in 2019 (14.5 T produced by an HTS coil in a background 18 T resistive field) [32.5T].

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 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 [FASUM] and subject of the EU design study SuperEMFL [SuperEMFL]. 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

[1] NI windings [https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7596694/] 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.

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, is directly relevant and applicable to progress in high field magnets for materials and life sciences.

Fusion magnets

TO BE COMPLETED

- Overview of conductor development in Europe within the scope of the EUROFusion DEMO activities (main results and challenges) and DTT (Central Solenoid inserts)
- NI magnets development and test at Tokamak Energy
- TFMC and development and VIPER conductors for pulsed operation in the US

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.

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 [MuCol, IMCC], the hadron-hadron future circular collider FCC-hh [FCC] and the Super Proton Proton Collider (SPPC) [SPPC].

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 and undulators, the technology developed, 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

TO BE COMPLETED: Marco, Sara and Gael to provide a short state-of-the-art

Medical applications

TO BE COMPLETED

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, DECODE). 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 DECODE. In this case, however, achieving TRL that would allow elicit strong industrial interest, so TRL 5 to 6, 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 demonstration 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 plans for the future 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. X1, 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.

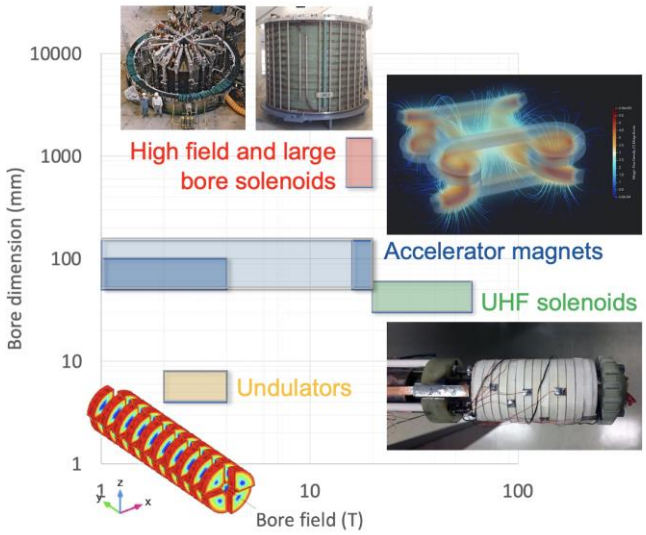

Figure X1. Schematic representation of the four HTS magnet challenges in terms of magnet bore dimensions vs.

bore field. Relevant design and magnet examples are shown to give an impression of the technology.

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. X2.

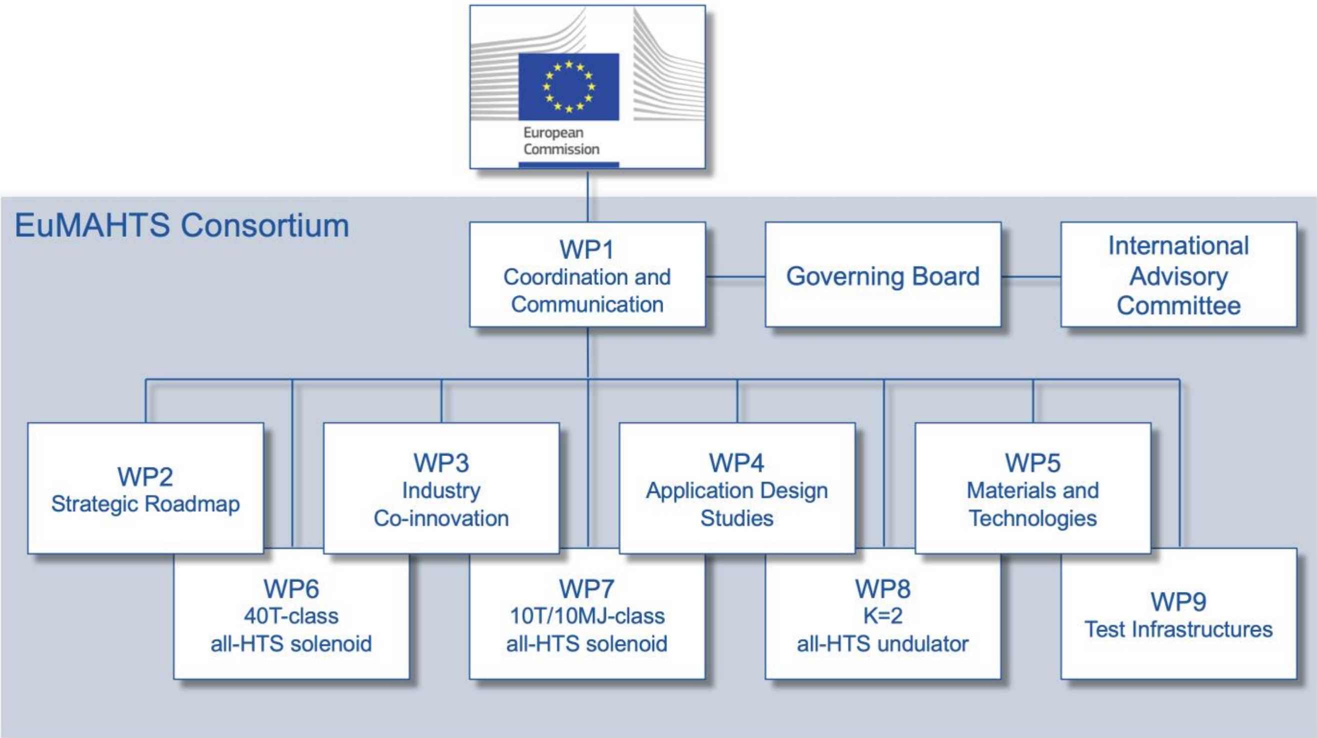

Figure X2. Structure proposed for the organization of work, management and governance of EuMAHTS.

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 50 mm bore. This solenoid would be 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 would be relevant for multiple other field of application. This prototype addresses mainly the engineering focus areas E1, E2 and E3;
- An all-HTS standalone solenoid (split or non-planar coil) targeting a field of 10 T with 500 mm bore, large stored energy and energy density. This solenoid could provide the background field for a new test facility for testing RF components, and the split would be relevant technology for 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 wehy EuMAHTS has identified critical technologies, whose development will run in parallel with thye 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 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* is an activity where industry and research institutes collaborate 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 provide continuous support and follow-up, experimental background, and access to facilities. This pursues programs initiated in the last years, such as AMICI and IFAST.

A first 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. A second requirement for selection is to benefit, if possible, the engineering and construction of the prototypes, also implying industry participation to those challenging realizations. Finally, co-innovation actions must have potential to generate immediate return to industry. This implies increased EU industrial capability in the novel field of HTS magnet technology, and is by itself a positive result.

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)
  - High Gradient HTS Magnets (main application: industry, Particle Physics)
- *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 our proposed methodsa

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, 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 associated to WP3.

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 earlt 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, we have decided to engage industry through the Pre-Commercial Procurement (PCP) mechanism. CIEMAT will take the role to develop and place a number of PCP contracts, one per action. We recall that CIEMAT has 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 a 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 CIEMAT has taken part in the last year. This market survey will be done by CIEMAT, with the help of AIPF and ILO 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 AIPF and 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, under the responsibility of CIEMAT. 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 Office at CIEMAT (General Secretariat) will support the EuMAHTS team on these procedures. Before placing the contracts, these procedures will be audited by the Legal Department of the Spanish Ministry of Science. 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 needs

We may consider subcontracting third parties for specific services of modest scope within the overall industry co-innovation activities. In particular, it is expected that a company expert in innovation procurements will be subcontracted for providing support to work the PCP contracting procedures in an efficient way, specifically, to define a contract format simple and with conditions adapted to the actual need of the co-innovation 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. X3.

Figure X3. 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 this work package also 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 and when 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 provide guidance for the industrial exploitation of the results of EuMAHTS beyond the completion of the project, which is also a task included in this work package. Excellent strategy documents are available for several of the fields of application of magnet technology, specifically HTS. Examples given in the references collected so far [2022-LDG], [2016-GOU], [2018-LEA], [2005-NAS], [2013-NAS] will be the starting point of the activity of WP2. Within this work package we wish to extend the process to other 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), 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, that we will integrate into a strategy document with a time horizon of ten years and two main functions. Internally, the strategic 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 strategic roadmap will be crucial to identify and promote investments and industrial exploitation (WP3). Externally, the strategic roadmap produced by WP2 will provide input to higher level strategic processes in Europe, and most likely worldwide. One such example is the upcoming process of European Strategy for Particle Physics (ESPP), due to start in 2025 and lasting about two years, i.e. well in line with the timing of activities foreseen for WP2.

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 resur 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 be in charge of 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 elaborates on the magnet challenges with a main aim to study design concepts, identify engineering limits and relevant R&D, and quantify the impact of HTS magnet technology in selected fields of application. In simple terms, the study activities within the scope of this work package will examine and quantify risk and gain in “what if” scenarios where HTS magnet technology plays a role. 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 tasks initially selected, their relevance and stakes are:

- 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 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, 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.

<u>WP6, WP7, WP8 – Prototypes</u>. 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;

- WP7: All-HTS split solenoid: 10T-class, 300 mm x 200 mm bore, 10MJ-class. The magnet will be operated at high cryogenic temperature, either dry- or gas-cooled;

- WP8: All-HTS K=2 undulator, with 2T gap field, 10 mm period and 5mm gap. : achieve 3 T gap field, with 8 mm period and 5 mm gap in an undulator demonstrator for next generation synchrotron light sources and FEL

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.

WP9 – Test Infrastructures. 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, 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 will provide high performance at lower energy consumption and lower cost, enabling new research infrastructures that would not be possible without this innovation.

A first example is for 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). A second example are 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). Another example are 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. Finally, 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 or transportation.

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 Expected 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. Other opportunities ?

2.2.3 Research data management and management of other research 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:

- Findability 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.

- Accessibility 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.

- Interoperability 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.

#§COM-DIS-VIS-CDV§#

2.3 Summary

KEY ELEMENT OF THE IMPACT SECTION

SPECIFIC NEEDS

What are the specific needs that triggered this project?

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 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 and societal applications, to be delivered to institutional and industry stakeholders

EXPECTED RESULTS

What do you expect to generate by the end of the project?

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 action, 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.

D & E & C MEASURES

What dissemination, exploitation and communication measures will you apply to the results?

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.

OUTCOMES

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

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 across 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

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

3.1 Work plan and resources

Timeline of milestones and deliverables, critical decision points

Resources summary, M+P

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. The Consortium will comprise in 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, in line with its mandate to coordinate at European level the efforts of R&D in accelerator physics and Technology. The goal of CERN's coordination will be to ensure coherence with the goals of the European R&D roadmap, in order to ensure that MuCol will deliver results that will critically impact the next ESPPU. CERN will also participate with in-kind resources in almost all the workpackages, and will serve as a host for the consortium for general meetings and events. CERN has a long experience in managing complex studies of Accelerator physics and technology, and has developed over the years tools for collaborative work that will be put at the disposal of the consortium.

The Consortium will comprise a balanced mix of Laboratories, some of them with specific competencies such as ENEA for liquid metal loops, and LNCMI for high field solenoids. Other laboratories have a vast experience and spectrum of competences in Accelerator physics and technology (e.g. INFN, CEA, UKRI, ESS). Finally the Consortium is complemented with Universities, that will provide the link to academia, will bridge the gap towards young generation of researchers, providing opportunities for direct dissemination through public lectures and seminars, and providing high level scientific support to the studies in MuCol, but also a platform to hire the reuiqred PhD students and PostDocs.

This large consortium will provide opportunities for discussion and exchange of know-how among experts, ensuring that all results will be peer-reviewed already internally because of the nature of the consortium itself. The contiguity with the larger International Muon collaboration, comprising also other universities and laboratories, and in particular institutes from US and Japan, will ensure that the progress and the results of MuCol will be of the highest quality standards.

Every institute has promised resources to MuCol and those resources will be committed through a Consortium agreement to be signed by every participant, to secure a sufficient level of Person Months to achieve the goals of Mucol and supervise the young researchers. Every workpackage is covered by more than one institution, this structure will ensure also a low level of risk since every Institute will be ready to take over more responsibilities in the unlikely case that one of the institutions will have to withdraw from MuCol.

In addition, several institutes forming the consortium have multi-disciplinary capacity, covering multiple of the above fields, and providing direct links to other national and EU initiatives, ensuring that EuMAHTS participants remain fully aware of progress and opportunities in the field.

#§CON-SOR-CS§# #§PRJ-MGT-PM§#

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

Table 3.1b: Work package description

For each work package:

Work package number	
Work package title	

Objectives

Description of work

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)

Table 3.1d: List of milestones

Milestone number	Milestone name	Related work package(s)	Due date (in month)	Means of verification

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§#