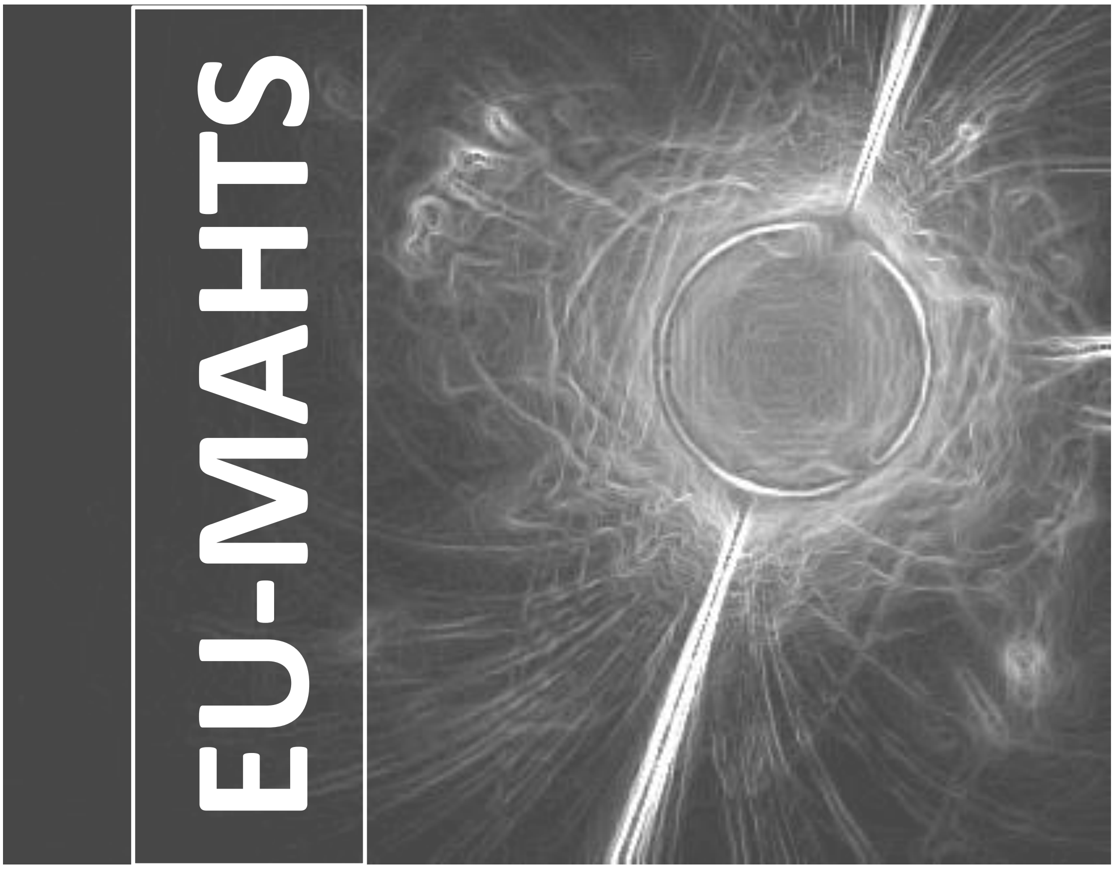
5 November 2023



***M**agnet **A**dvances through **H**igh **T**emperature **S**uperconductors*

Background to the proposal

Nearly forty years after their discovery [ref HTS discovery], High-Temperature Superconductors (HTS) are finally 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 [ref Bruker 1.2 GHz, 32T NHMFL], a keen interest in the use of high field magnets for compact fusion reactors as part of the energy transition [ref MIT/CFS], which in turn has driven cost reduction coming from large investment at manufacturing sites [ref SuperOx review], and heightened awareness on the importance of long-term sustainability [ref SCGA].

The commonplace definition of HTS materials is to exhibit superconducting properties at higher temperatures when compared to low temperature superconductors (LTS). This makes them more practical for various applications, avoiding some of the engineering complexity of cryogenics. In reality, however, it is truly the sum of several properties that is driving a high interest in this magnet technology:

- HTS magnets can generate exceptionally strong magnetic fields, surpassing by far the capabilities of conventional and LTS magnets, and opening the path to a new range of application in research, material and life sciences, energy generation and transportation. These applications would not be possible without HTS;

- HTS materials also allow for the design of smaller and lighter magnet systems that surpass the performance of conventional and LTS magnets. Compactness can result in lower system cost for the same performance, or higher performance for the same cost;
- Finally, HTS magnets can be operated at temperature higher than LTS magnets. They can hence achieve higher energy efficiency and lower power consumption, as well as lower cryogen inventory (or a different cryogen), making HTS magnets environmentally friendly and cost-effective over the long term.

The perspective applications of HTS magnets are multiple, straddling several fields of science and societal applications. To cite only the most prominent:

- Research and Science: HTS magnets can significantly enhance scientific research by enabling more powerful and compact devices, such as particle accelerators for high-energy physics research, light sources with improved analysis power, and high magnetic field user facility for material and life sciences.
- Healthcare and Life Sciences: HTS magnets are expected to enhance analysis devices like NMR (Nuclear Magnetic Resonance) and medical imaging devices like MRI (Magnetic Resonance Imaging) machines, 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 a simplified cryogenics.
- 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 play a critical role in creating the magnetic fields necessary for plasma confinement in compact machines.
- 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.

Magnet challenges where HTS would make a difference

It is possible to find significant commonalities among the potential of HTS magnet technology to meet the demands originating from the various and diverse fields of science and societal applications quoted earlier. We give below a broad description and a synthesis of the main technical targets of four grand magnet challenges that exemplify well the envelope of such demands. We also include in the discussion below some considerations on the relevance to specific fields of application.

- Ultra-high field (UHF) HTS solenoids, with small bore, in the range of 50 mm, and field range of 40 T and higher. This is well above the reach of LTS, which is slightly in excess of 20 T. Such magnets would be of interest for material science in high magnetic field, UHF NMR for life sciences, and high energy physics experiments such as a muon collider. The technology developments, and in particular achieving high current density, sound mechanics, and quench management, would also be relevant for light sources, neutron scattering, compact fusion magnets, generators and motors.

- High field (HF), HTS solenoids with large bore, 1 m diameter, and field range around 20 T, also considering operation at cryogenic temperatures well above liquid helium, e.g. 10 to 20 K. This is also beyond the reach of LTS solenoids, but fields at this level and higher can be achieved with hybrid systems consisting of an external superconducting solenoid and internal resistive solenoid, though on a significantly smaller bore, few cm, and large power consumption, in the range of tens of MW. Such magnets are relevant for fusion, high energy physics experiments such as the muon collider and potentially for different hybrid technology as combination of HTS and resistive solenoids. For this class of magnets it is especially important to stress energy efficiency as a key performance indicator.
- HTS dipoles and quadrupoles for beam lines and accelerators, with field ranging from modest values (a few T) to high values (e.g. 20 T), bores in the range of 50 mm to 200 mm, and operating in the range of temperature of 10 K to 20 K. At the high end of the performance specifications, these are the magnets that could enable future colliders such as a 100 TeV FCC-hh or a 10 TeV muon collider. At the same time, such technology would also profit nuclear physics applications, light sources, medical accelerators and gantries by providing a robust and low energy consumption solution in the range of low to medium field. The technology devised for the 3D winding (ends) would also provide useful solutions for non-planar coils of large dimensions, such as stellarators for magnetically confined fusion. These accelerator magnets would need to be compact, and high engineering current density, to limit cost. The development of compact, high current density and high-field pole windings would profit other fields of applications such as superconducting generators and motors.
- High field HTS undulators and *superbends*. These are two classes of magnets that share the need to generate sharp field variations over short longitudinal distances. Achieving such fields is important to increase the performance of light sources and free electron lasers. A challenging target for undulators is achieving a field of 3 T in the gap, with short period, 8 mm to 10 mm, and a gap of 5 mm which is presently a standard for this type of magnets. In the case of superbends a good target is a peak field of 10 T with a longitudinal field integral of 1 Tm. Coil winding technology for these magnets is likely to be similar to that of UHF solenoids, and beam line magnets, discussed earlier, with a clear synergy among these developments.

The four magnet challenges described above have in common the fact that adopting “all-HTS” solutions will bring improved performance, profiting from the exceptional critical properties of HTS. Most important, an all-HTS magnet can operate at temperature higher than liquid helium, resulting in improved energy efficiency and reduced cryogen inventory.

The field range and magnet dimension of the four challenges described above are represented in Fig. 1, which gives a visual confirmation that the spectrum of characteristics identified covers a large parameter space. We are hence confident that our analysis truly covers the whole frontier of HTS magnet technology.

Finally, Fig. 2 reports an intersection of relevance between the magnet challenges and the field of scientific and societal applications discussed earlier. Technology development for the four magnet challenges will be of direct relevance for several fields at once, demonstrating synergy and integration.

<u>Within the scope of this proposal we will study technical solutions towards the four magnet challenges defined above, define relevant technology development, and quantify impact (WP2).</u>

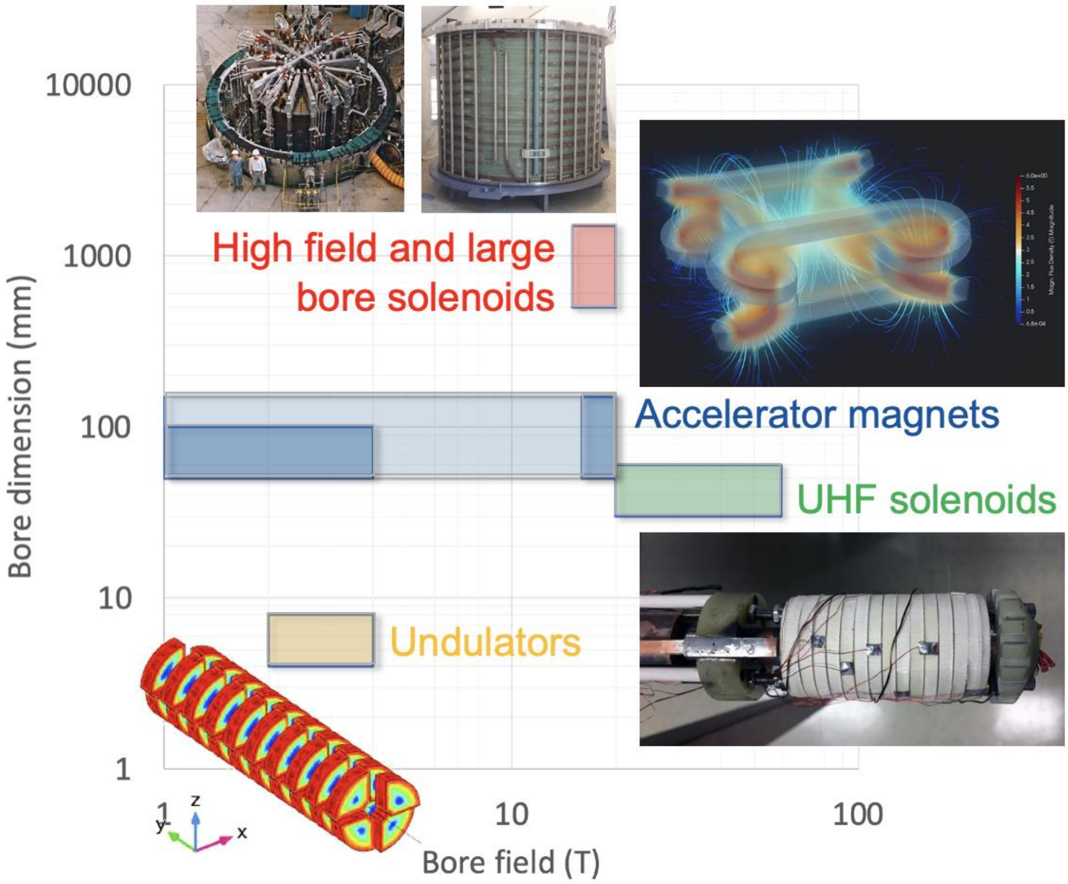
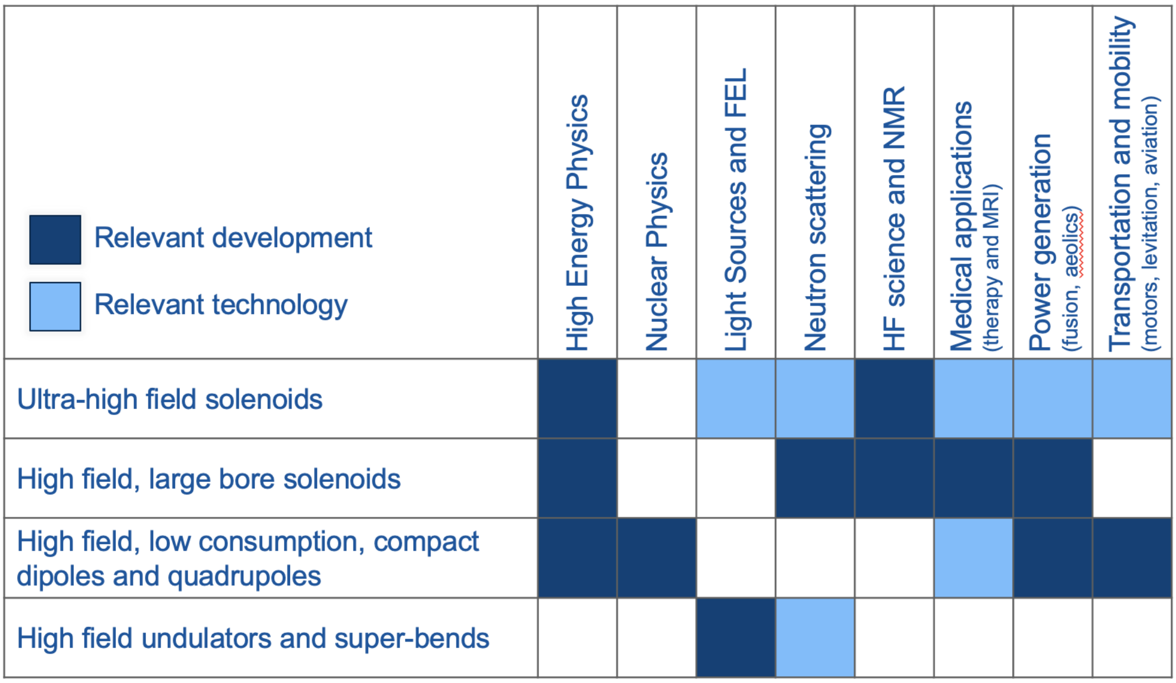


Figure 1. Schematic representation of the four HTS magnet challenges in terms of magnet bore dimensions vs. bore field. Relevant design and magnet examples are shown to give an impression of the technology.



■ Relevant development

▨ Relevant technology

	High Energy Physics	Nuclear Physics	Light Sources and FEL	Neutron scattering	HF science and NMR	Medical applications (therapy and MRI)	Power generation (fusion, aeolics)	Transportation and mobility (motors, levitation, aviation)
Ultra-high field solenoids	■		▨	▨	■	▨	▨	▨
High field, large bore solenoids	■			■	■	■	■	
High field, low consumption, compact dipoles and quadrupoles	■	■				▨	■	■
High field undulators and super-bends			■	▨				

Figure 2. Schematic representation of the relevance of the four HTS magnet challenges towards applications in multiple fields of scientific and societal applications of HTS magnet technology.

The need for technology development

The perceived potential of HTS magnet technology illustrated above, and exemplified by the four magnet challenges, explains the strong motivation for development that we are witnessing these days in several fields of science and societal applications. The present state of this technology is however still at a relatively low TRL level, namely around TRL3 (experimental proof of concept) approaching in some cases TRL4 (technology validated in lab conditions). An advance is still required to come to a TRL level suitable for industry to engage and integrate this new technology into products, namely reaching TRL5/TRL6 (technology validated/demonstrated in industrially relevant environment). This is exactly the core of this proposal, aiming at increasing the TRL of HTS magnet technology by two units.

In the path towards the above objective, we recognize first that there are fundamental differences between HTS and LTS. Indeed, it is very likely that optimal use of HTS in a novel magnet technology will require a *paradigm shift* in design and manufacturing. Some examples of features requiring such paradigm shift are:

- The fact that HTS have extraordinary critical properties, much beyond those of LTS, whereby the critical temperature, field and current are no longer limiting factors in the design and operation of a magnet;
- The inherent stability of HTS to external perturbations, orders of magnitude higher than that of LTS, which eliminates the issues of *stability and training*. This however makes quench detection and protection much more difficult than in LTS;

- The possibility to wind HTS coils with controlled resistance between turns, in the form of non-insulated (NI) windings, which increases the engineering current density of the coil and can contribute to solving the issue of quench protection;
- The fact that most technical HTS materials with high performance come in the form of tapes on a sturdy mechanical substrate, thus requiring an innovative approach to making high current cables and winding coils.

Addressing the above challenges will need significant advances in magnet science and technology, with large inherent innovation potential. Hence, not only the direct results would have great values in terms of magnet technology, but also the progress in design concepts, engineering tools and manufacturing technology will have a sizeable net worth, beyond specific magnet applications.

In order to profit from the exceptional features of HTS materials, we are aware that we need to develop and master new technology. Below the result of our analysis of the most critical technologies:

- Energy efficient and sustainable cryogenic technology. Energy efficiency can be achieved by developing effective cooling means for operation at temperature significantly higher than liquid helium, e.g. 10 K to 20 K, thus also reducing the cryogen inventory, and possibly opening the path towards alternative cryogens such as hydrogen;
- HTS cables and conductors technology. All applications quoted will likely require improvements in the mechanical and resistive properties of HTS, which is presently the true limitation to achieving and boosting performance in magnets. Also, using parallel of single conductors may be needed to improve robustness against degradation, and reduce inductance to simplify powering and quench management. High current cables and conductors, in the range of 10 kA to 50 kA, will be required for magnets with large stored energy, such as large bore solenoids and long accelerator and beam line magnets;
- HTS winding technology. Several of the best performing HTS conductors come in the form of tapes, and winding non-planar, 3D coils will require development of designs and techniques. Such winding can be insulated or non-insulated, where by insulation and inter-turn resistance control will need development. Magnet mechanics and supporting structures for novel winding shapes will have to be devised, as well as techniques for joints and terminations. Finally, HTS windings will be compact and high current density to profit the most from the high critical current. This will require novel quench management schemes, including both quench detection and energy dump.
- Diagnostics, sensors and control technology. Already mentioned above, new quench detection methods may be mandatory for HTS magnets. In fact, early detection of resistive transitions may fundamentally change quench management strategy. This may be achieved by acquiring signals other than voltage. Furthermore, direct field control and integrated field correction may be required to compensate field lags, drifts and errors associated with current diffusion and screening currents;
- 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.

The technologies identified above will provide the substrate necessary to advance and validate the design of the four magnet challenges. This is pictorially illustrated in Fig. 3, showing the meshing of HTS magnet challenges with the required advances in technology.

The work proposed here includes the required R&D to achieve such advances (WP3).

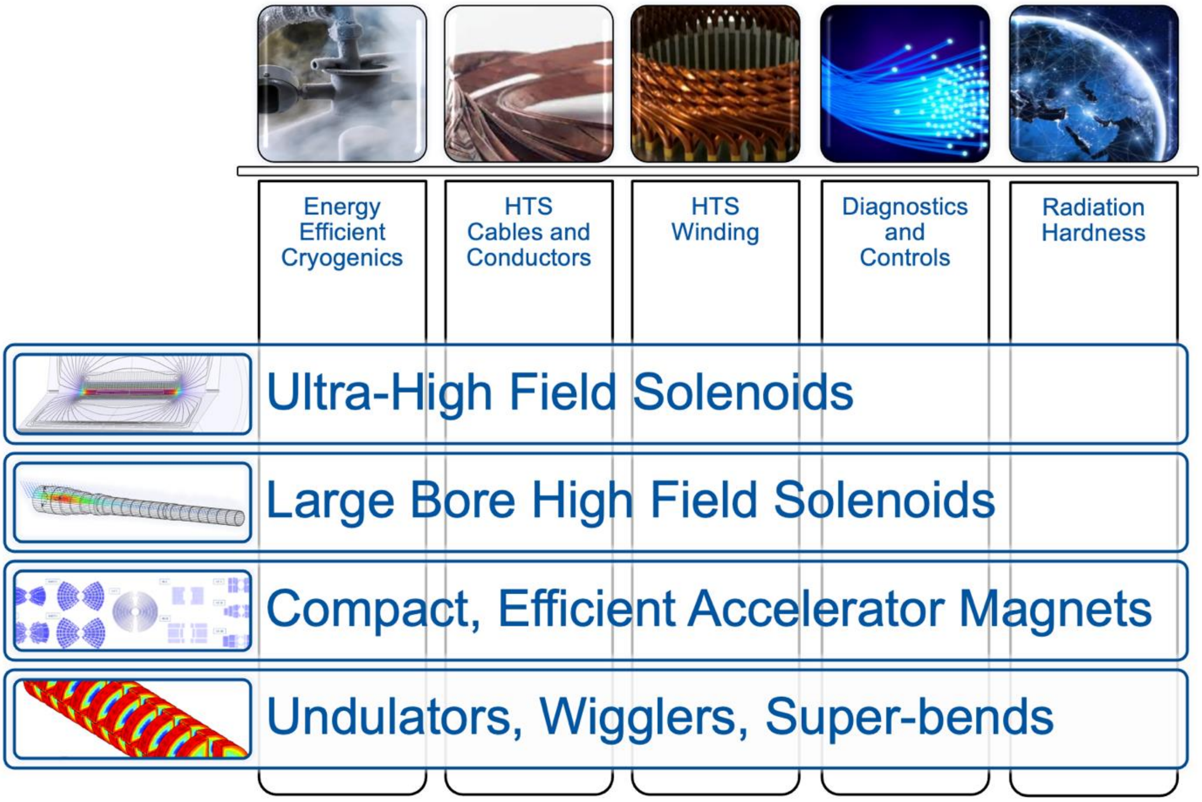


Figure 3. Schematic representation of the meshing among the four HTS magnet challenges and relevant advances in relevant technologies.

The need for demonstration

Achieving significant TRL advances in HTS magnet technology will depend critically on practical demonstrators, where new design principles and methodologies are applied and validated. Such demonstrators are magnets, with performance beyond the state of the art, addressing following key steps:

- Validation and Proof of Concept: Rigorously demonstrate HTS functionality and reliability in real-world conditions;
- Reproducibility: Verify consistent and reliable results;
- Scalability: Ensure that the technology can be scaled up to meet industrial demands;
- Cost-Efficiency: Assess capital and operational costs, highlighting the cost-effectiveness of HTS;

- Market Acceptance: Signal readiness to investors, collaborators, and customers for support and partnerships, showcasing the potential of HTS magnets.

At the same time, we are aware that designing, building and testing relevant HTS demonstrator is material and labor intensive, and we recognize that it will not be reasonably possible to build all magnets to the scale identified earlier. We hence focus our work on three demonstrator with the smallest possible scale, still with most relevance for all fields of applications.

The demonstrators proposed can be regarded as engineering templates for the first-of-a-kind of an industrial production, and should be used in field to show that they can provide advanced capability in the specific field of science (WP4).

The proposed demonstrators are the following:

- 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;
- 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. In addition, if non-planar features are introduced, the coil would demonstrate capability towards stellarators;
- An all-HTS small period undulator with 3 T gap field, 8 mm period and 5 mm gap. This HTS demonstrator would produce field well beyond the state of the art, as required for next generation synchrotron light sources and FEL.

Solenoid model coils built with modest conductor lengths and size (few km) can probe performance limits at extreme values:

- Field (20 T…40 T) – high and ultra-high field characterization of the critical surface JC(B,T,a);
- Force and stress (500 MPa…700 Mpa) – engineering test at levels relevant and beyond full-size accelerator magnets;
- Current density (600 A/mm2…900 A/mm2) and energy density (300 MJ/m3) – quench detection and protection in a new regime, where present technical solutions do not work (detection time would be too short, quench heater power would be too high);
- “Simple” engineering, fast turnaround.

Description of the proposal

Top-level objectives

Advance HTS technology to a point sufficient to realize its perceived potential, bridging the gap between laboratory realizations and deployment. This requires an increase of TRL by two units, i.e. from TRL 3…4 (laboratory demonstration) to TRL 5…6 (demonstration in industrial relevant environment).

Develop technology required for the next step in HTS magnets.

Build and test demonstrators that will be *engineering templates*, usable in-field, and first-of-a-kind for industrial production.

Work packages

The work package and task structure is shown schematically in Fig. 4.

WP1 – Coordination and Communication

The scope of this work package is to ensure organization, coordination of activities and appropriate communication among all work-packages and participants.
This work package consists of the following tasks:

- Organization, coordination and communication
- Follow-up of schedule and cost
- Administrative and documentary support
- Project meetings and events

WP2 – Strategic Roadmap

The scope of this work package is to develop an inclusive strategic roadmap for HTS magnet technology that matches needs from the various fields of activity represented in the project. Previous strategy documents of relevance (initial list) are:

- European Strategy for Particle Physics
- CohMag and SciMag
- Neutron Spectroscopy
- EU Fusion roadmap
- SC Global Alliance:

WP3 – Industry Cooperation

Activities in this work package are directed to support participation of industry, organization of internal tender actions and follow-up of industrial studies, design and manufacturing (i.e. demonstrators). The Industry Cooperation workpackage relies on existing coordination and structures such as the TIARA Accelerator - Industry Permanent Board.

WP4 – HTS Magnets Applications

This work package elaborates on the four magnet challenges, by reviewing the magnet challenges with respect to the field of potential applications, study design concepts, identify issues and relevant R&D, quantify impact. The study activities within the scope of this work package consider the following fields of application of HTS magnet technology:

- Energy efficiency and sustainability
- High Energy Physics applications
- Nuclear Physics applications
- Light Sources and FEL applications
- Neutron scattering applications
- High Field Science and NMR
- Medical applications, including therapy and MRI
- Power generation, including fusion and aeolics
- Transportation and mobility, including motors, levitation and aviation

WP5 – Materials and Technologies

Success in HTS magnet engineering depend critically on advances in specific area of material science and technology. This work package groups the activities devoted to understanding needs, performing R&D and producing novel design and manufacturing solutions with respect to:

- Energy efficient and sustainable cryogenic technology, considering cryogenic fluids and cycles for high temperature (10 K to 20 K), heat management (dry, indirectly cooled, gas cooled,…), and minimal cryogen use at reduced fluid inventory
- HTS cables and conductors technology, in particular characterization and improvement of electro-mechanical properties of HTS, high current cables and conductors (10 kA to 50 kA), and cables for DC and ramped (AC) magnets
- HTS winding technology, for various types of coils (planar and non-planar coils), including considerations on interturn insulation or interturn resistance control, joints and terminations, and electro-mechanical solutions for high-current-density and high-energy-density windings as required for compact coils, in particular for quench management
- Quench detection and protection, given the extraordinary challenges, is defined as an activity of its own, integrated in the overall development
- Diagnostics, sensors and control technology, specifically for quench detection (voltage and other techniques) and magnetic field control (field shaking, field feedback)
- Radiation properties and radiation hardness, with particular focus on HTS superconductors

WP6 – Demonstrators

The activities in this work package cover the demonstrators, specific magnets, including engineering design, construction and testing. Each demonstrator represents a significant effort and investment and is hence covered by a sub-work package structure

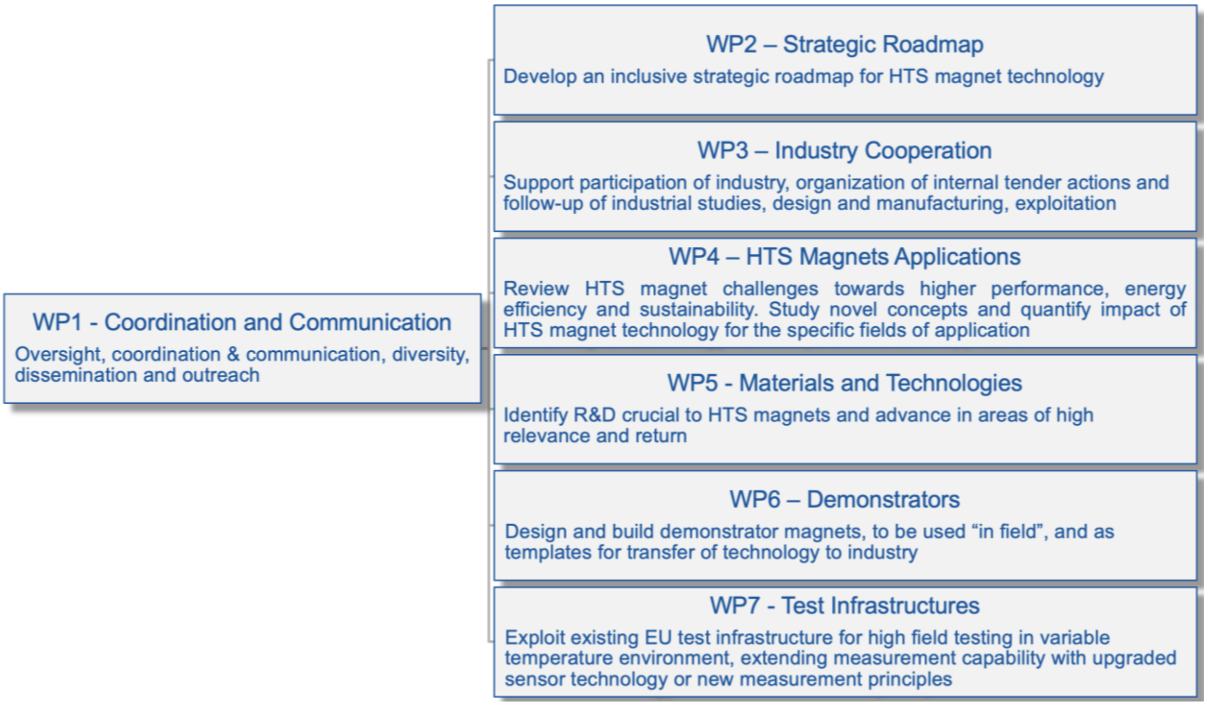
- WP6.1 – All-HTS ultra-high field solenoid: achieve 40 T in a 50 mm bore solenoid, compact winding, high engineering current density
- WP6.2 – All-HTS standalone background field for laboratory testing: achieve 10 T in a 500 mm bore, split magnet with large forces, stored energy and energy density. Relevant technology for split and super-bends in a beam line (note – 3D ?)

- WP6.3 – All-HTS small period undulator : 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

WP7 – Test infrastructures

Test infrastructures and test methods are instrumental to the success of the work proposed. This work package covers the activities required for characterization and test, for materials, R&D and demonstration purposes. We wish here to exploit at best existing EU test infrastructure with minimal adaptation or upgrade, in particular:

- High field testing, to measure the electro-mechanical and thermo-physical characteristics of superconducting and resistive materials, cables, and small-size coils
- Variable cryogenic temperature installations, to explore operation in different conditions of cryogenic heat transfer and cooling
- Sensors and measurements for the characterization and test of novel materials, technologies and demonstrators will likely require to upgrade sensing technology or new measurement principles



WP1 - Coordination and Communication

Oversight, coordination & communication, diversity, dissemination and outreach

WP2 – Strategic Roadmap

Develop an inclusive strategic roadmap for HTS magnet technology

WP3 – Industry Cooperation

Support participation of industry, organization of internal tender actions and follow-up of industrial studies, design and manufacturing, exploitation

WP4 – HTS Magnets Applications

Review HTS magnet challenges towards higher performance, energy efficiency and sustainability. Study novel concepts and quantify impact of HTS magnet technology for the specific fields of application

WP5 - Materials and Technologies

Identify R&D crucial to HTS magnets and advance in areas of high relevance and return

WP6 – Demonstrators

Design and build demonstrator magnets, to be used “in field”, and as templates for transfer of technology to industry

WP7 - Test Infrastructures

Exploit existing EU test infrastructure for high field testing in variable temperature environment, extending measurement capability with upgraded sensor technology or new measurement principles

Figure 4. Provisional work package structure and main objectives.