Future Superconducting Magnet Technology

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Task 4.3: Preparation of a proposal for a R&D&I programme on Smart Diagnostics

TITLE : Smart Wireless Diagnostics for Superconducting and Cryogenic Applications

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1 EXCELLENCE

1.1. Context and Objectives

These days we are party to an unusual expansion in the development of embedded electronics under the popular name "Internet of Things" (IoT).
The IoT designation is used to cover the networking of physical devices, vehicles, home appliances, and other items embedded with electronics, software, sensors, actuators, and connectivity which enables these things to connect, collect and exchange data. IoT involves extending Internet connectivity beyond standard devices.
The electronics industry is delivering to the market new products each day with enhanced characteristics in respect of power consumption and connectivity together with wireless communications, trying to satisfy the demand from consumers and developers for more sophisticated IoTs. The availability of new and more performant electronic sensors for acquiring a wide variety of physical signals has exploded the later years.
Almost regardless of the industry branch, IoT is predicted to be the single most important factor affecting fundamental business logic in the coming decades.
Fancy marketing words and geek gadgets apart, IoT is successful because the driving forces behind this demand are efficiency and convenience.
Several long-awaited solutions for efficiency and convenience around automation and logistics are now possible because the state of the technology for wireless embedded electronics is mature enough and commercially effective; this is why IoT is a success story.
Acknowledging this situation, this proposal aims to take profit from it and push the limits further to use this vision in the harsh environments of low temperatures. To "virtualise" the highly complex instrumentation and profit from the new Big Data technologies and Artificial Intelligence to reduce significantly the required time to gain "expert experience" from the superconducting magnets. This will allow us to understand and solve the problems we are facing at the technology edge of superconductors.

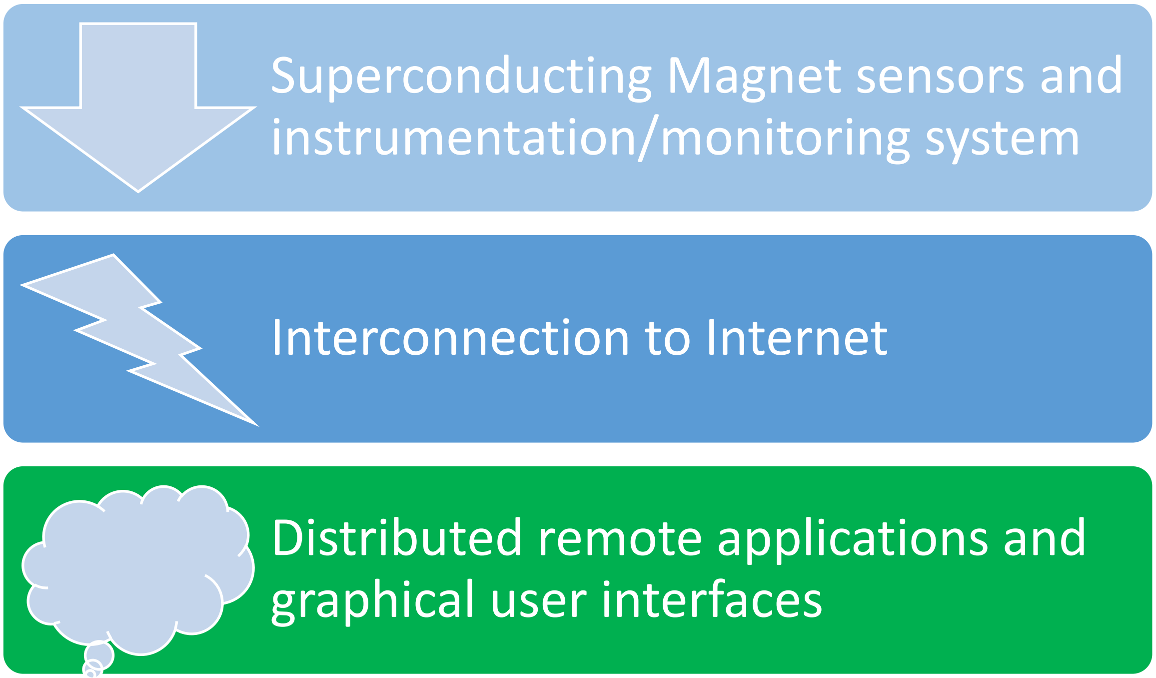
The reference to low temperatures within the document refers to temperature levels of the cryogenic thermal shields, in the order of 70 K to 50 K, or below.

In marketing terms, the objective is to transform a superconducting cryogenic magnet (or a cryogenic vessel with equipment inside) into an IoT device. In more academic terms, it is to take measurements with embedded electronic instrumentation, confined inside a cryogenic vessel and interconnected via wireless links.

1.2. Description

The monitoring and control of superconducting magnets is electronics based. An electronics instrumentation system is interconnected to appropriate sensors placed in the appropriate places inside and outside the cryostat. The acquired values are electronically transmitted to the monitoring and control units which act in response.
In a first step to apply the IoT vision, we can group the required functionalities in three layers:

- Sensors and Instrumentation
- Interconnection to Internet
- Distributed remote application and graphical user interfaces



We use the term “Smart Wireless Diagnostics” to refer collectively to the 3 layers covering the set of all the systems and functionalities, which makes possible the remote monitoring, diagnostics and control of a superconducting magnet via Internet technologies.

In this vision, the instrumentation/monitoring system is the part which obtains real-time data and feeds one or more connection points, which relays the information via the Internet. The storage and analysis of the collected data is distributed to remote data centres. The user receives the information via various graphic user interfaces (such as smart phones, tablets or intelligent screens) which connect to these data centres. The data handling and analysis at the remote data centres is done using the technologies such as Neural Networks, Artificial Intelligent, Deep Learning, Big Data Analysis, etc.

The actual solutions for monitoring, diagnostics, control and protection are based on electronics located outside of the superconducting magnet at ambient temperature as the existent systems will not work at a low temperature.

To connect the sensors inside the superconducting magnet to the diagnostic systems outside, special wires are used which cross the different temperature layers and mechanical interfaces. This crossing of the thermal layers requires complex mechanical interfaces.

The restrictions imposed by the complexity of the mechanics and in wiring sensors together generally results in minimal instrumentation not even capable of providing data in real-time most of the time.

One of the aims of this project is to break these restrictions, to have more and different types of sensors that are better and faster in collecting real-time data which is analysed and processed with modern technologies.

Ambition

The long-term objective is to access a superconducting magnet efficiently and conveniently from remote devices (like smart phones, tablets or intelligent screens). Provide abundant and high precision data for the monitoring, diagnostics, control and protection functionalities, with real-time algorithms using intelligent applications such as Neural Networks, Deep Learning, Artificial Intelligent, etc.

To make this real, the ambitious step forward of this program is to have the instrumentation electronics embedded inside the low temperature vessel with the powering and communication provided by wireless links.

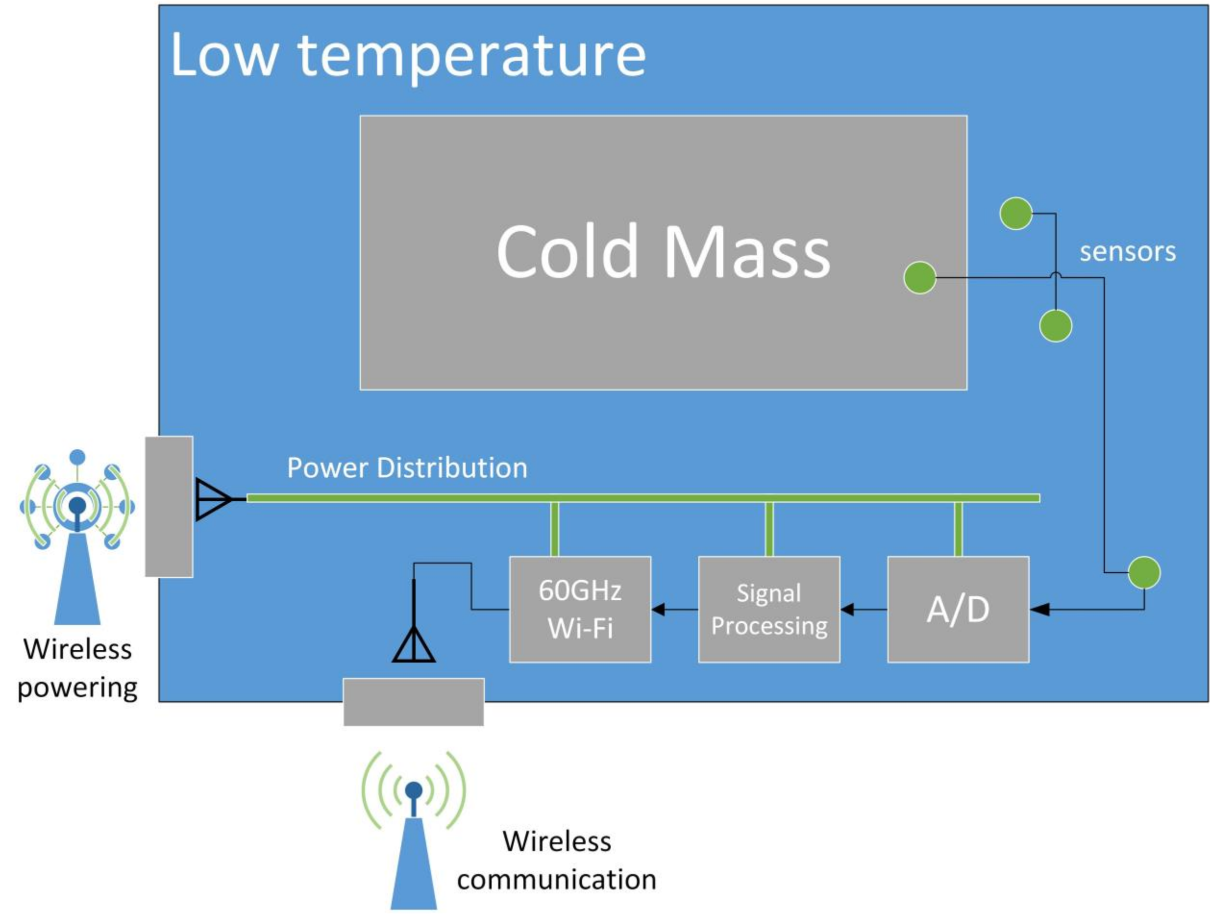


Fig.1

In this proposal, as a first phase of the long-term objective, the electronics embedded inside the cryogenic vessel continue to rely on wires for the interconnections between sensors and the instrumentation, as well as for the interconnection with the power distribution. However, there are no wires going outside the vessel. The wireless communication link is to be used to connect to an Internet point, allowing the data to be collected and analysed by remote devices.

As show schematically in Fig.1, there is a wireless link for the data and another for power from inside to outside the vessel, with wired interconnections confined inside.
This compromise gives a lot of freedom for the mechanical and thermal design and an achievable objective within an horizon of 4 years. Leaving for a future phase the extension to wireless interconnections also for sensors and other elements inside the cryogenic vessel.

This limitation of scope, to the first layer and part of the second layer, automatically reduces the resources required in terms of personnel, time and money. Leaving part of the second layer and the third, which are mainly based on Internet and information technologies, to a future complementary proposal.

The advantages granted by having embedded electronics working at low temperature confined within the cryogenic system are several:

a) The mechanical and thermal design of the cryogenic vessels do not need complex inserts for the instrumentation. This reduced complexity allows designer to produce simpler mechanics, more reliable and with lower production costs.

b) Opens the possibility to easily have more measurement points. Additional sensors do not add wires to the exterior, they only require an interconnection inside the vessel. More measurement points allow better analysis, better modelling, better monitoring and better control of the equipment.
c) The instrumentation can be placed locally, closer to the physical source. The short distances between the sensors and the electronics will permit a better integration, with a reduction of noise in the measurement, more precision and greater accuracy.
d) The instrumentation becomes an inherent functional part of the device. In the sense that once installed in the cryostat, the confined electronics are an integral part of the equipment. You don't manipulate, transport or service, two separated entities but one.
e) Data is always easily available, independent of the equipment state or place, being at the factory, at the workshop, in transport or in operation. A smart device with a wireless link is the only requisite to monitor and check the equipment, no need of external equipment to branch or plug.
f) Data storage, monitoring, analysis and processing are decentralised and accessible via the Internet technologies.

1.3. Methodology

The scope of the proposal is

- the selection, modelling and test of suitable electronics components capable of working at low temperatures
- the selection, modelling and test of suitable sensors capable of working at low temperatures
- the selection, modelling and test of suitable materials capable of mechanical rigidity and low radio frequency absorption to build small radio frequency "windows" or antennas at the interface of the cryogenic vessel.
- the selection, modelling and test of the suitable material for gluing and building Printed Circuit Boards capable of operating at low temperature.
- the design, modelling, building and testing of the embedded electronic systems for the instrumentation, the wireless communication and the wireless powering.

These works include disciplines related to materials and electronics coupled with low temperature environments.

The desired configuration of the electronics, inside the cryogenic vessel, requires reducing the servicing to the minimal, even if possible, go for no-servicing. Thus, the design should follow high reliability and high availability guidelines, as in "mission critical" equipment.

The realisation of the different task requires the setup of a low temperature electronics laboratory. For this the actual members of the FuSuMaTech Consortium : CERN, CEA and Oxford Instruments, are prepared to engage resources.

The initiative for a materials database and test facilities list planned by FuSuMaTech will benefit this proposal.

This proposal is open for more partners willing to collaborate.

Persons in the research of micro-electronics in harsh environments but not members of FuSuMaTech Consortium have been contacted and expressed very limited interest in the proposal.

Prof. Hans K. Soltveit from Heidelberg Universitet is interested in providing his Wireless Data Transfer (60GHz) custom integrated circuit (IC) for the wireless link and test its performance at low temperature for data in designing an improved version.

Prof. Paul Leroux and Prof. Filip Tavernier, from the KU Leuven, at the ESAT and MICAS laboratories are only interested for the case of developing custom microelectronics for low temperature environment as is Dr. Juha Hassel from VTT Technical Research Centre of Finland Ltd.

2 IMPACT

2.1. Expected Impact

Applications already existing using a low temperature environment will gain in performance, simplicity, efficiency and convenience.
Several applications that previously were impossible to construct because the instrumentation required was not able to be confined, will now be possible.
Other applications for which the real-time data and sensing information was insufficient for their control, due to the lack of embedded electronics at low temperature, will also be possible.

2.2. Potential Applications / Market

The applications that use low temperatures in their environment are increasing. The new researches into "Quantum computers" are based on cryogenic environments. Medical devices such as MRI are based in superconductors at low temperature. Research accelerators and colliders are relying more and more on superconducting magnets at cryogenic temperatures. Superconducting generators for windmills are starting to be discussed. The wider extension of electrical networks and the increase in consumed power are reaching the point where the savings resulting from the use of superconductors at cryogenic temperature start to be economically interesting. The intelligent transport of liquefied gases in pipelines at low temperature is in need of smart instrumentation. Aerospace devices are naturaly working in a low temperature environment.
All of these applications will benefit from embedded electronic instrumentation working at low temperatures, which will also help to reduce their complexity. The reduction in complexity will allow for the reduction in size and cost, which in turn increases the scope for application of the devices.

3 IMPLEMENTATION

3.1. Work plan and Roadmap for Development

The work has been separated in “electronics”, “materials” and “integration”.

For the “electronics”, four sub-tasks has been planned, to provide the constitutive elements of the embedded electronic instrumentation system:

1. the sensors required by superconducting magnets
2. the electronics for reading the and processing the data
3. the electronics for the wireless communication link
4. the electronics for the wireless powering

The elements will be designed and tested separately, in accordance with an interface definition for their interconnection.

The development of each “electronics” sub-task will be carried out in five phases:

I. design of the initial electronic topology and circuits
II. selection of potential electronic parts
III. study, testing and validation at low temperature of the selected parts (far beyond their commercial thermal operating point)
IV. prototyping (and mitigations, if necessary), adapting the initial circuit design to the parts finally chosen
V. final prototype unit

With a deliverable at the end of each phase (success indicator)

The realisation of the sub-tasks could be executed in parallel as there is no need to wait for results from one to develop the other.

For the first two phases the time line is 1 year, for the third 1 year and for the last two also 1 year.

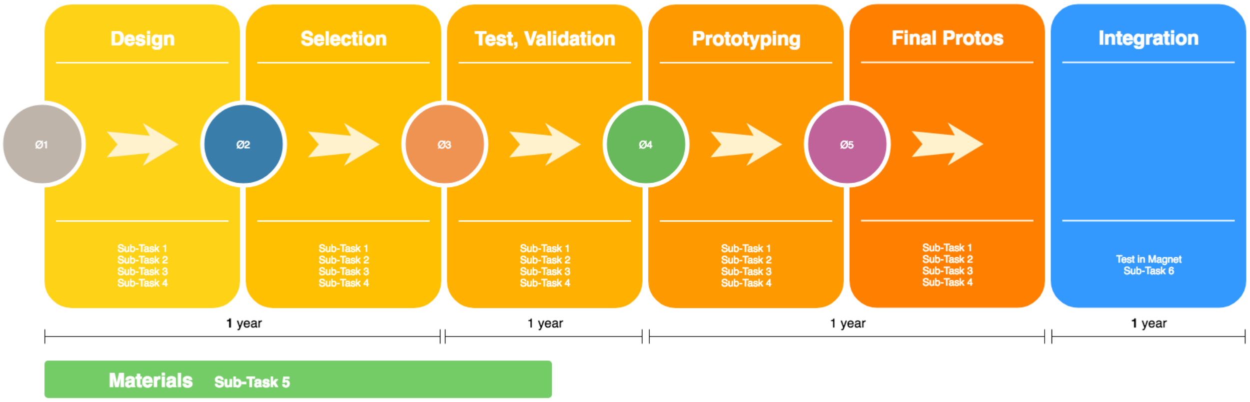


Fig.2 roadmap

For the “materials”, one sub-task has been planned, to test or develop the following materials needed

- the material for the radiofrequency “window” or antenna used at the interface of the superconducting magnet
- the materials and adhesives used for the PCB

The time line for this is 1.5 years.

For the “integration”, one sub-task has been planned, carry on the integration of all the parts and test of embedded electronic instrumentation in a superconducting magnet prototype or a cryogenic vessel. The anticipated time line is 1 year.

3.1.1 List of Sub-Task

The list is

1. electronics 1
2. electronics 2
3. electronics 3
4. electronics 4
5. materials
6. integration

3.1.1.1 Sub-Task Description

As mentioned earlier, the “electronics” Sub-Tasks will comprise the development of electronics that will be carried out in five phases:

- I. design of initial electronic topology and circuits
- II. selection of potential electronic parts
- III. study, testing and validation at low temperature of the selected parts (far beyond their commercial thermal operating point)
- IV. prototyping (and mitigations, if necessary), adapting the initial circuit design to the parts finally chosen
- V. final unit prototype

It is possible to define a deliverable at the end of each phase (success indicator) or to fix this only for the end of phase III and phase V, depending upon which is the more important.

Sub-Task 1, electronics 1 - sensors

Even if only one sensor is the minimum needed for this project, a maximum number should be studied and tested to have a broad catalogue to select from for the different needs of the superconducting magnet community.

This Sub-Task should test as much sensors as possible and provide at least one sensor prototype capable of:

- working reliably at a low temperature in the superconducting magnet environment
- with power dissipation and consumption optimized
- capable of delivering an electrical signal that can be used by the measurement electronics

The sensors should be selected among the several different types of transducers and sensors used within superconducting magnets. And produce an electrical signals compatible with electronics measuring systems.

A non-exhaustive catalogue includes :

- a) strain gauges, used to measure mechanical deformation and mechanical vibrations.
- b) temperature probes, mainly thermocouples (2 wires as well as 4 wires), used to measure temperature.
- c) main coils voltages (at different points), to calculate losses, electrical continuity, material state or as indirect way for other physical values like current or magnetic field.
- d) fibre optic sensors, mainly based on Fabry Perot interferometry (FP) and on Fibre Bragg Grating technology (FBG) used as an indirect measurement for different environmental conditions of the cryostat.
- e) quench antenna or pickup coil, used to measure magnetic fields
- f) accelerometers, used to measure mechanical movements and vibrations
- g) acoustic sensors, used to detect mechanical vibrations or pressure changes
- h) pressure sensors, used to measure mechanical forces or gas pressures
- i) flow meters, used to measure fluid flows

j) current or di/dt sensor, used to measure current

The information from these signals is not limited for monitoring, diagnostics and protection of the superconducting magnet. They are also used in the understanding of the physical processes occurring within superconducting magnets, build mathematical models, understand the performance limitations and improve the magnet design.

Sub-Task 2, electronics 2 - control, acquisition and data processing

This Sub-Task must provide an electronics unit be capable of

- working reliably at a low temperature in the confined superconducting magnet environment
- reading the electrical signals delivered by several sensors
- processing the sensors signals
- control the element provided by Sub-Task 3, wireless communication link, and produce the high precision real-time data stream to feed it
- working with power dissipation and consumption optimized

The architecture for this type of system is generally constructed around a signal conditioning stage, an Analogue to Digital Converter (ADC), some digital “intelligence” with or without memory and digital signal processing stage.

The signal conditioning stages transform the signals from the sensors to a suitable form for the ADC.
The digital “intelligence” is normally a microcontroller, microprocessor or programmable logic, with the signal processing is performed by a Digital Signal Processor (DSP).
COTS electronics from different vendors, different technologies and different functionalities are widely available for these parts (to work at ambient temperature).
The catalogue of the studied COTS electronics with their measured behaviour at low temperature will be delivered to the FuSuMaTech Consortium.

Sub-Task 3, electronics 3 - wireless communication link

This Sub-Task must provide an electronics unit capable of

- working reliably at a low temperature in the confined superconducting magnet environment
- working with power dissipation and consumption optimized
- performing wireless data transmission, through an RF transparent material, to a wireless network point located outside the superconducting magnet.
- interconnection with the element provided by the Sub-Task electronics 2.

This is one of the key elements of the project. The ability to transmit in real-time the data generated inside to the outside of the confined area is a critical requirement. Without wireless transmission the data must use wires and this forces the use of complicated inserts.

COTS electronics from different vendors, different technologies and different protocols are widely available to construct wireless communication links working at ambient temperature.
In addition, there are two custom integrated circuits (IC) one designed by CEA and other by the Heidelberg Universitat in the 60GHz band that could be used for this unit.

It is important to note that the choice of frequency band selected in this Sub-Task will impact in the requirement for the Sub-Task materials in terms of the characteristics of materials to use.

Several parameters will be set by this Sub-Task, which defines the communication link, including frequency band range, coding modulation and protocols.

Sub-Task 4, electronics 4 - wireless powering

This Sub-Task must provide electronics units for transmission and reception capable of

- for the reception, working reliable at a low temperature in the confined superconducting magnet environment
- working with power dissipation and consumption optimized
- transmit a wireless signal, through an RF transparent material, strong enough to power the embedded electronics confined inside the superconducting magnet or cryogenic vessel. (The load is expected to be the elements provided by Sub-Tasks electronics 1, electronics 2 and electronics 3).

The wireless powering source will be outside the cryogenic vessel at room temperature.
Only the receptor will be inside at low temperature.
COTS electronics from different vendors, different technologies and different standards are available for wireless powering solutions (working at ambient temperature).
It is important to note that the choice of frequency band selected in this Sub-Task will impact in the requirement for the Sub-Task materials in terms of the characteristics of materials to use.

Several parameters will be set by this Sub-Task, which defines the power transmission link, including frequency band range, and standard.

Sub-Task 5, materials

This Sub-Task covers the materials, not related to electronic components, necessary for the project.
This Sub-Task needs to test and research materials capable of

- supporting the mechanical characteristics required at the interfaces of the superconducting magnet
- have low radio frequency absorption

A small “window” or antenna is required at the interface to the cryogenic vessel that allows only the radio frequency signal to cross and maintains the sealing.
The accepted radio frequency attenuation and radio frequency range will be set by Sub-Task electronics 3, wireless communication link, and Sub-Task electronics 4, wireless powering.
It could be possible that two different materials are used, one for the requirements of Sub-Task electronics 3 and other for Sub-Task electronics 4.
The mechanical requirements at the interface of the superconducting magnet, stress, shock, deformation, life, etc… will be set by the Sub-Task integration according to the characteristics of the superconducting magnet or cryogenic vessel prototype chosen.

This Sub-Task needs to test if the COTS materials used to build Printed Circuit Boards are capable to operate at low temperature, including their soldering and gluing. If not it needs to research for suitable materials.

Sub-Task 6, integration

This Sub-Task integrates all the developed parts to provide a functional embedded electronic instrumentation confined in the superconducting magnet prototype or cryogenic vessel decide by the FuSuMaTech Consortium.

3.1.1.2 Sub-Task Resources

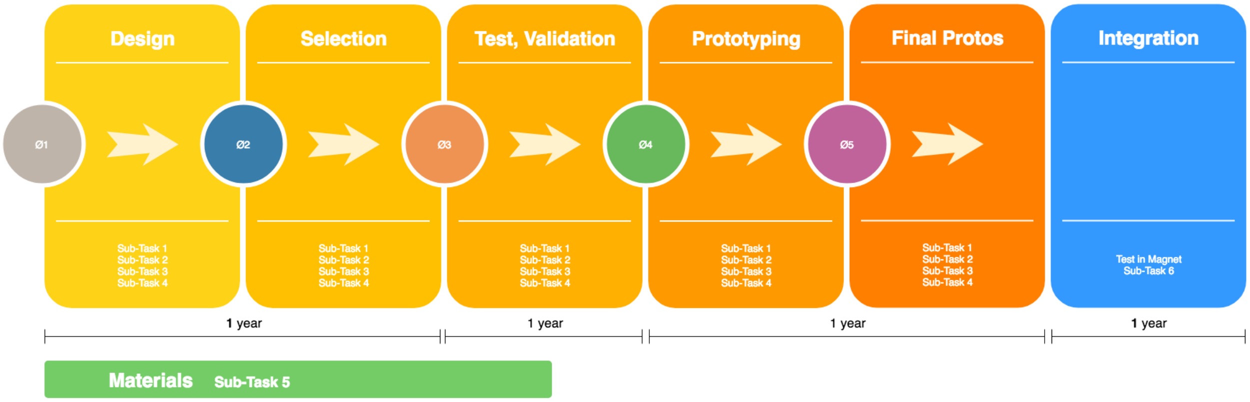
In addition to the developments described above, the measurements and characterisations require a generic low temperature electronics laboratory facility, “use of installation” refers to the use of this kind of installation.
Some tests will require the design and construction of simple electronics for support of the components to be studied. A magnet test facility able to give nominal working conditions will be required for the final steps.

Estimated costs in Euros

	Sub-Task 1	Sub-Task 2	Sub-Task 3	Sub-Task 4	Sub-Task 5	Sub-Task 6	
	3 years	3 years	3 years	3 years	1.5 years	1 year	
Material	100K	200K	150K	150K	80K	100K	
Manpower	150K/year	250K/year	180K/year	180K/year	180K/year	150K/year	
Use of installation	80K/year	80K/year	80K/year	80K/year	80K/year	80K/year	
Total	790K	1190K	930K	930K	470K	330K	4640K

The skills required for the Manpower are in the fields of design and construction of electronics, research in materials and low temperatures environments.

3.1.2 Roadmap



The deliverables will be

For Sub-Task 1, electronics 1, - sensors

- (at end of phase 3) a catalogue containing the studied sensors with the results of the tests
- (at end of phase 5) the prototype/s of sensor/s,

For Sub-Task 2, electronics 2, - control, acquisition and data processing

- (at end of phase 3) a catalogue containing the studied electronic components with the results of the tests
- (at end of phase 5) the prototype of control , acquisition and data processing unit

For Sub-Task 3, electronics 3, - wireless communication link

- (at end of phase 3) a catalogue containing the studied electronic components with the results of the tests
- (at end of phase 5) the prototype of wireless communication unit

For Sub-Task 4, electronics 4, - wireless powering

- (at end of phase 3) a catalogue containing the studied electronic components with the results of the tests
- (at end of phase 5) the prototype of wireless powering unit

For Sub-Task 5, materials

- a catalogue of the studied materials and their characteristics
- a list of selected materials that fulfil the requested requirements and the material characteristics to order their production

For Sub-task 6, integration

- delivery of the final prototype

3.1.3 Risk Analysis

For the execution of the project a roadmap including milestones and deliverables is proposed to follow the progress and detect divergences from the baseline and start corrective measures (if needed) to complete the objective in time and budget.
From the unknowns a major risk of this research is that the objective to have all the embedded COTS electronics working reliably at a low temperature is not achieved.
In this case, custom electronics with special semiconductor processes for low temperature use will be required.
If this is not possible, then the alternative is to have the electronics on the exterior, at room temperature. This is not a satisfactory solution for an advanced research program as this is the actual applied solution for existing superconducting magnets. So, this failure would shut down this program.

A secondary low-level risk is that the power dissipation of the confined electronics is greater than the cryogenic capacity of the magnet or vessel, making the system inefficient.
Mitigations for this risk could be:

- increase the cryogenic capacity.
- change topologies to optimise and reduce the power dissipation.
- prevent a continuous operation of the electronics.
- reduce the electronics by minimizing available functionalities.

A third risk is to not achieve the electronic part for the wireless transmission in powering and/or data at low temperature. This failure will force the use of wires which will degrade the final objective but will not halt the program.
A non-completely confined measurement system inside the cryostat is still of high interest due to the advantages of the low temperature electronics.

3.2. Consortium (role, activity of each Partner within the project)

CERN role : Coordinator
CEA role : Partner
Oxford Instruments role : Partner

3.3. IP Matrix Review and status

No IP has been received as a contribution and in principle, there is no IP required as pre-requisite for this proposal.
If any IP is generated by this research, it will belong to the partner carrying out the research with a special grant allowing its use by the other members of the FuSuMaTech Consortium in their products.

The information from the sensors and electronic devices studied at low temperature, in this project, will be loaded into the database of the FuSuMaTech Consortium.