EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Brussels, 23 June 2017

COST 029/17

DECISION

Subject: **Memorandum of Understanding for the implementation of the COST Action "NANOSCALE COHERENT HYBRID DEVICES FOR SUPERCONDUCTING QUANTUM TECHNOLOGIES" (NANOCOHYBRI) CA16218**

The COST Member Countries and/or the COST Cooperating State will find attached the Memorandum of Understanding for the COST Action NANOSCALE COHERENT HYBRID DEVICES FOR SUPERCONDUCTING QUANTUM TECHNOLOGIES approved by the Committee of Senior Officials through written procedure on 23 June 2017.

MEMORANDUM OF UNDERSTANDING

For the implementation of a COST Action designated as

COST Action CA16218
NANOSCALE COHERENT HYBRID DEVICES FOR SUPERCONDUCTING QUANTUM TECHNOLOGIES (NANOCOHYBRI)

The COST Member Countries and/or the COST Cooperating State, accepting the present Memorandum of Understanding (MoU) wish to undertake joint activities of mutual interest and declare their common intention to participate in the COST Action (the Action), referred to above and described in the Technical Annex of this MoU.

The Action will be carried out in accordance with the set of COST Implementation Rules approved by the Committee of Senior Officials (CSO), or any new document amending or replacing them:

a. “Rules for Participation in and Implementation of COST Activities” (COST 132/14);
b. “COST Action Proposal Submission, Evaluation, Selection and Approval” (COST 133/14);
c. “COST Action Management, Monitoring and Final Assessment” (COST 134/14);
d. “COST International Cooperation and Specific Organisations Participation” (COST 135/14).

The main aim and objective of the Action is to use the fundamental knowledge obtained in superconducting systems to control the main superconducting parameters in devices and produce radically new behaviour. NANOCOHYBRI will lead a European effort, using open-minded and simple instruments, to promote exchanges that contribute to avoid duplication of resources and develop the emerging quantum world. This will be achieved through the specific objectives detailed in the Technical Annex.

The economic dimension of the activities carried out under the Action has been estimated, on the basis of information available during the planning of the Action, at EUR 72 million in 2016.

The MoU will enter into force once at least five (5) COST Member Countries and/or COST Cooperating State have accepted it, and the corresponding Management Committee Members have been appointed, as described in the CSO Decision COST 134/14.

The COST Action will start from the date of the first Management Committee meeting and shall be implemented for a period of four (4) years, unless an extension is approved by the CSO following the procedure described in the CSO Decision COST 134/14.

TECHNICAL ANNEX

OVERVIEW

Summary
Superconducting technologies are prime candidates to ripen quantum effects into devices and applications. The accumulated knowledge in decades of work in understanding superconductivity allows scientists now to make experiments by design, controlling relevant parameters in devices. A new field is emerging whose final objective is to improve appliances taking advantage of quantum effects, be it for dissipationless transport of current, generation of high magnetic fields, sensors or quantum information. The field will impact crucial areas for societal development, including energy, transport, medicine or computation. Quantum behavior is controlled by using hybrids of superconductors with magnets, insulators, semiconductors or normal metals. Traditionally, the scientific and technical communities working in superconductivity are spread across projects from different calls, whose activities put Europe at the frontier of research. The present Action aims to address the pressing need for a common place to share knowledge and infrastructure and develop new cooperative projects.

To this end, we have set-up a program including networking activities with an open, proactive and inclusive approach to other researchers and industry. We will develop the concept of a Virtual Institute to improve availability of infrastructure and knowledge, and focus on contributing to gender balance and the participation of young researchers. The proposal aims to avoid duplication of resources and skills in a subject traditionally dominated by small groups working independently. This will optimize European efforts in this area and uncover our full potential, thus maintaining and developing Europe's leading position in superconducting quantum technologies.

Areas of Expertise Relevant for the Action	Keywords
● Physical Sciences: Superconductivity (theory) ● Nano-technology: Superconductivity for nano-technology applications ● Chemical sciences: Chemistry of condensed matter ● Physical Sciences: Instrumentation - telescopes, detectors and techniques ● Physical Sciences: Nanophysics: nanoelectronics, nanophotonics, nanomagnetism or classify	● Superconducting nanostructures and materials ● Controlling phase, flux and charge in nanoscale devices ● Hybrids made of superconducting and magnetic systems ● Vortex physics and driving current through superconductors ● Low temperatures-high magnetic fields-ultrafast measurements

Specific Objectives
To achieve the main objective described in this MoU, the following specific objectives shall be accomplished:

Research Coordination
● To achieve a common ground to use superconducting quantum coherence.
● To enable a new generation of applications of superconductivity, including current carrying and quantum information devices, by controlling superconducting parameters at the nanoscale.
● To build and test new devices based on a precise control over dimensionality, geometry and interaction with the quantum condensate.
● To develop a collaborative effort, crosscutting experiment and theory, using the full potential of European research in superconductivity.

Capacity Building

- To bridge the gap between traditionally separated scientific communities that have complementary knowledge and a common interest in superconducting devices.
- To train the next generation of stakeholders in a growing field that will lead to the next quantum revolution.
- To educate engineers and society, making it more commonplace to think in terms of the possibilities enabled by technologies utilizing quantum coherence.
- To provide a platform for young European researchers to build an efficient network.
- To foster contribution from researchers from inclusiveness target countries and facilitate their participation in high level European calls.

1) S&T EXCELLENCE

A) CHALLENGE

I) DESCRIPTION OF THE CHALLENGE (MAIN AIM)

The last century left us with the conceptual framework to understand and handle macroscopic quantum coherence. Superconductivity is an established form of macroscopic quantum coherence that surprises regularly the scientific community with new discoveries and has already created new markets thanks to the dissipation less transport of electrical current. We can expect a quantum leap in the societal impact of superconductivity during the coming decades through current carrying applications as well as novel quantum technologies.

NANOCOHYBRI is triggered by the amount of fundamental knowledge obtained in superconducting systems and the recently acquired ability to control magnetic flux, and electron charge and spin in devices. Much of the topical research in this area is being carried out all over Europe in the subfields of low dimensional systems, hybrids between superconductors and magnets or semiconductors, and nanoscale engineering for current carrying applications. The scientific and methodological approaches in these fields are similar and there is an important potential for cross-fertilization. The challenge is to use the understanding achieved and control the main superconducting parameters in devices to produce radically new behaviour. In order to address this challenge, NANOCOHYBRI will join efforts and form a European size network, open-minded and managed within simple rules, promoting exchanges among stakeholders. NANOCOHYBRI will contribute to avoid duplicating efforts and resources, thus developing the full possibilities of European science in the emerging quantum world.

II) RELEVANCE AND TIMELINESS

Superconductivity is a macroscopic quantum phenomenon realized in the solid state. It therefore provides all the advantages of scalability and large scale production that have made semiconducting technology so useful. At the same time, superconductivity offers radically different functionalities through its quantum coherence. Efforts are mostly conducted bottom-up by groups of researchers dispersed in many different laboratories and companies throughout Europe—from small university groups obtaining insight through academic approaches, to large scale research activities involving hundreds of engineers and scientists; from garage-like start-ups to activities promoted by large companies. These efforts are funded by excellence programs (ERC at European level and national programs), programs for emerging technologies (FET) or initiatives on large scale infrastructure. The common denominator is, unfortunately, that they are carried out independently.

There is thus a high risk of multiplying scientific and technical efforts within Europe without improving the outcome for European citizens. NANOCOHYBRI addresses this problem by providing a flexible networking scheme, organized within simple rules, that allows for frequent meetings and exchanges among researchers all over Europe. NANOCOHYBRI is fundamentally open, according to COST rules, providing the flexibility to address the most pressing and timely questions and includes interested researchers and engineers. In that way, the Action will combine the resources and knowledge needed to make sure that European science reaches its full potential.

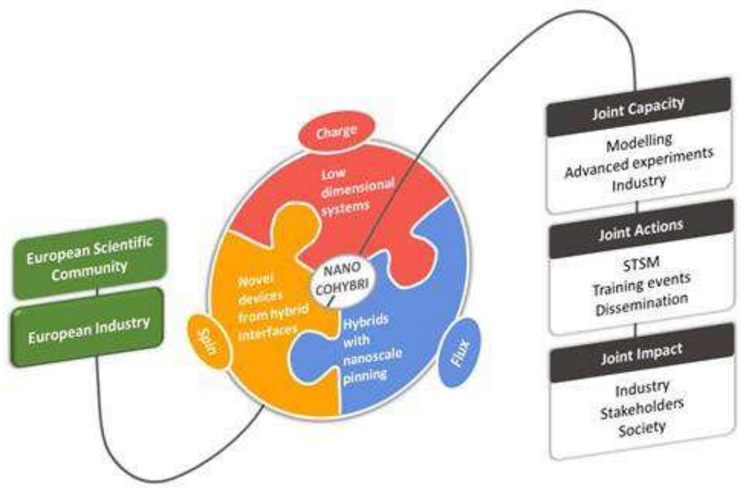
Quantum behaviour in general is still considered by many scientists and engineers somewhat "spooky". While we have learned to imagine improvements in our lives in areas utilizing mechanical or electromagnetic principles (e.g. drones, robots or internet connectivity), the principles of quantum mechanics are still too far from our everyday living experience. Superconducting applications, be it levitating trains or quantum computers, produce a considerable fascination and are counterintuitive. All participants in this Action use this fascination to interest people during dissemination activities, making spectacular demonstration experiments (such as superconducting levitation). However, the other side of the coin is that the society as a whole, including stakeholders all over industry, policy and finance, still view quantum phenomena and in particular superconductivity as a technology for "nerds" and "ivory tower scientists" of limited use. But the fact is that there exists a consolidated industry based on superconductivity and the opportunities, as exemplified in this proposal, are much broader. If Europe aims to succeed in the quantum revolution which is flourishing world-wide, there is a pressing need to render superconductivity into a widely spread source of inspiration. This Action will provide activities fostering exchange of information and resources, helping to educate and train engineers and scientists alike and bringing superconductivity closer to the society.

B) SPECIFIC OBJECTIVES

I) RESEARCH COORDINATION OBJECTIVES

- To achieve a common ground to use superconducting quantum coherence.
- To enable a new generation of applications of superconductivity, including current carrying and quantum information devices, by controlling superconducting parameters at the nanoscale.
- To build and test new devices based on a precise control over dimensionality, geometry and interaction with the quantum condensate.
- To develop a collaborative effort, crosscutting experiment and theory, using the full potential of European research in superconductivity.

II) CAPACITY-BUILDING OBJECTIVES



- To bridge the gap between traditionally separated scientific communities that have complementary knowledge and a common interest in superconducting devices.
- To train the next generation of stakeholders in a growing field that will lead to the next quantum revolution.
- To educate engineers and society, making it more commonplace to think in terms of the possibilities enabled by technologies utilizing quantum coherence

- To provide a platform for young European researchers to build an efficient network.
- To foster contribution from researchers from inclusiveness target countries and facilitate their participation in high level European calls.

C) PROGRESS BEYOND THE STATE-OF-THE-ART AND INNOVATION POTENTIAL

I) DESCRIPTION OF THE STATE-OF-THE-ART

It was long debated if superconductors of sizes smaller than the characteristic length scale for the size of Cooper pairs could exist at all. Saint James and de Gennes examined already in 1963 the surface of a superconductor and found that superconducting regions should nucleate there at magnetic fields so high that the superconductivity would disappear in the bulk. A year later, Ginzburg found that surface states in an insulator might well hold superconductivity and that surface vibrations and screening could lead to interactions favouring superconductivity. If a two-dimensional superconductor might exist at all was also questionable. Mermin theorem stated that thermal fluctuations destroy long range order at any finite temperature. However, this year's Nobel Prize winners Kosterlitz and Thouless found (nearly at the same time as Berezinskii did independently) that superconductivity can occur in two dimensions thanks to bound pairs of vortices and antivortices. They established a new universal theory for phase transitions, largely used in the dawn of the 21st century to classify phases of matter by using their topological properties.

The twentieth century has produced tools and methods to create simple and controlled two dimensional materials. Among other materials, the dichalcogenides, the high critical temperature cuprate and pnictide superconductors have layers including different atomic species, with thickness of order of a nm. Superconductivity also appears at interfaces made of insulators and is then confined close to the interface. Emergence of high critical temperature superconductivity seems to be inherently connected to the existence of two dimensional electronic correlations in these layers. The two families of high Tc materials known so far, cuprate superconductors and the iron pnictides, are layered materials with quasi two-dimensional Fermi surfaces. The resulting high electronic anisotropy favors spin and charge instabilities, which are key ingredients in raising Tc. H. Kroemer pointed out in his Nobel lecture that "the interface is the device", referring to the new functionalities for high speed and opto-electronics opened by his work on fundamental properties of semiconductor heterostructures. In the same way, low dimensional superconductors are likely to play a relevant role in quantum technologies, because they offer unprecedented control over the shape of the superconducting order parameter.

Hybrid systems combine a superconductor with a ferromagnet, a semiconductor or a small quantum dot system. Cooper pairs are induced into the non-superconducting system through the proximity effect and produce a variety of coherent spin and charge configurations, relevant for both fundamental issues and applications. For instance, hybrid superconductor/ferromagnetic systems provide induced triplet pairing. When used in a junction geometry (superconductor/ferromagnet/superconductor), π junctions are formed that can be used to improve SQUID technology and quantum computation, providing new ways to couple superconducting loops to cavities. Furthermore, these junctions can be used as effective spin filters for spintronics and for energy efficient memories.

Vortex lattices have been studied for many years. It has been shown only recently, however, that simulations are able to address realistically vortex dynamics and that we have the means to test their validity through well controlled experiments. At the same time, old paradigms, such as the need to operate cuprate superconductors at liquid nitrogen temperature, are being overcome. Applications of current carrying devices at 4.2 K are becoming interesting, because of the considerable increase in the critical field with respect to classical low temperature superconductors. Furthermore, new capacities to utilize hybrid technology by introducing normal inclusions into the superconductor are now available and can be used to fine tune the value of the critical current.

II) PROGRESS BEYOND THE STATE-OF-THE-ART

We identify three themes where advanced innovation and cutting edge research is taking place in the field:

- Low-dimensional hybrid systems. Thin films or layered materials deposited on substrates lead to systems with modified bandstructure and sometimes considerably improved superconducting parameters (possibly thanks to phonons of the substrate). By shifting the chemical potential over a wide range, correlated states can be controlled to a large extent, leading to new symmetry breaking fields, such as charge order, structural transitions, broken spin-degeneracy due to spin-orbit interaction and new unconventional superconducting properties.
- Novel devices from hybrid interfaces. Interfaces between superconductors and ferromagnets lead to oscillatory behaviour of the order parameter, enabling π-junctions. Oxide interfaces provide a new and excellent opportunity to explore order parameter issues in devices for phase-sensitive experiments. Hybrids between superconductors and topological insulators provide a platform very likely hosting chiral superconductivity and Majorana fermions.
- Hybrids with nanoscale pinning particles of controlled size and shape enhance vortex pinning at high magnetic fields. Unprecedented control over the positions of quantized flux can be achieved through advanced nanostructuring, for instance by inhomogeneous electric fields in hybrids or by manipulating flux with optical or magnetic tweezers.

III) INNOVATION IN TACKLING THE CHALLENGE

To our knowledge, this is the first time that a network is formed to address the construction of superconducting devices and control quantum behaviour. This requires bringing together experts from different areas, including physicists, materials scientists and engineers. For example, quantum information devices based on superconductors rely on simple materials such as Nb or Al. By using unconventional superconductors as building blocks for novel devices we expect a variety of interesting properties to appear—such as improved protection from the environment. Bringing together experts in devices with experts in materials science and theoreticians is instrumental to exploit the new behaviour. NANOCOHYBRI aims to gather some of the most advanced European groups in microscopy (using new ultra-high resolution methods), with materials science groups (engineering landscapes), with groups manufacturing devices by advanced nanofabrication methods (such as focused ion beam deposition and milling) and groups modelling superconducting behaviour from microscopic (Bogoliubov-de Gennes) and macroscopic (Ginzburg-Landau) approaches.

D) ADDED VALUE OF NETWORKING

I) IN RELATION TO THE CHALLENGE

COST has shown to be a successful scheme to promote networking in communities that would otherwise remain separated. While the European efforts in the subject are ample, there exists no network covering the mainstream fields aiming to build devices that benefit from the different aspects of macroscopic quantum behaviour.

By setting an active program of meetings and exchanges, within the open and simple scheme of COST, this Action will enable collaborations among different communities and promote dialogue among researchers with widely different background. For instance, experts in microscopy will work to understand vortex pinning processes in devices and in cables, or engineers will design nanofabricated devices integrating unconventional superconductors, with the help and guidance of advanced theoretical calculations. The common goal of improving appliances using quantum behaviour is sufficiently wide to inspire researchers having different approaches to join efforts and exploit the common background. This will help to develop a common language and improve the visibility of the field to industry and the society as a whole.

II) IN RELATION TO EXISTING EFFORTS AT EUROPEAN AND/OR INTERNATIONAL LEVEL

Europe is very competitive in the design of devices for quantum technologies, is leading efforts in obtaining and manipulating topologically protected states at interfaces, and has achieved outstanding superconducting high critical temperature material and considerable success in advanced instrumentation in the field, covering aspects such as microscopy or photon detection. These efforts are carried out within a number of European projects, ERC projects and also projects with a large industrial participation (for example FP7-NMP-Large-2011-280432 EUROTAPES, EU FP7 FoF-ICT-2013 FORTISSIMO, FP7-ENERGY- 2009-1-241285-2 ECCOFLOW, FP7 NMP 2011 EU-Japan Superiron, Iron-Sea, Suprapower, FP7-Energy 2012 or Ecoswing H2020-LCE-2014-2). No active project of collaborative nature within a lightweight scheme as the one proposed by COST is available from 2017 on.

Among the previous collaborative projects, there is a series of Actions within the extinguished ESF scheme (Vortex action, Nanoscience and Engineering in Superconductivity-NES, which is a scheme for international networking with USA and Japan, see for instance http://www.kuleuven.be/inpac/nes/conferences.html), that have obtained a large number of continuous collaborative results through exchanges over the years. A COST Action on nanoscale superconductivity (MP1201, Nanoscale superconductivity: novel functionalities through optimized confinement of condensate and fields) has been running during past four years. The Action has served to achieve novel functionalities of patterned systems. The present proposal aims a radical step forward, using the obtained understanding and novel functionalities to design devices that bring quantum technologies to the next step.

The forecast of including quantum behaviour into real world applications is not unique to this Action and is been debated largely worldwide. The most obvious European effort in this area is the Quantum Technology flagship. The European Commission has decided to reinforce the European scientific leadership and excellence in quantum research and in quantum technologies and outlined the objective to launch €1 billion Quantum Technology Flagship in 2018 (see e.g. https://drive.google.com/file/d/0B8TwJOtGVL5lWVhaRE1nWTIwNkk/view). In the Quantum Technologies Roadmap 2016 superconducting circuits are explicitly mentioned as a very promising option for quantum devices with the best performance up to the quantum limit close to real applications. A Virtual Institute about quantum computation (http://qurope.eu/vi/q-comp) is included in the initiative. The present Action will support mutual synergies and ensure a high level participation from the community of superconductors into the flagship. Furthermore, among the proposals for future flagships, there is an ongoing initiative, by now mostly including stakeholders from the applied superconductivity community (https://ec.europa.eu/futurium/en/content/superconductors) which aims at developing superconducting technologies. Again, the collaborative efforts in NANOCOHYBRI can be expected to positively contribute to the development of this and related efforts.

2) IMPACT

A) EXPECTED IMPACT

I) SHORT-TERM AND LONG-TERM SCIENTIFIC, TECHNOLOGICAL, AND/OR SOCIOECONOMIC IMPACTS

The improvement of our understanding of superconductors during past years has been considerable and promotes the general feeling that the community is ready to move forward and fabricate devices with unprecedented control over superconducting parameters. In the short term, accumulation of evidences for unconventional superconductivity in low dimensional superconductors will lead to devices exploiting their unique new phase and spin behaviour. Improvements in nanofabrication show superconducting properties in several systems with a strong potential for novel applications and sensors. We can model vortex dynamics within realistic situations and many researchers already think of the critical current as a property that can be designed.

In the long term, NANOCOHYBRI is likely approaching to the goal of a technology where quantum effects, as absence or dissipation and quantum information are widely used in many appliances. For example, in improving energy generation and transport through current carrying devices and levitation, in improving imaging technology for medicine with new detectors and high magnetic field coils or in quantum computers.

B) MEASURES TO MAXIMISE IMPACT

I) PLAN FOR INVOLVING THE MOST RELEVANT STAKEHOLDERS

The stakeholders include scientists active in superconductivity, vortex physics, hybrids with proximity induced superconductivity, superconducting quantum technologies, materials science, and current carrying applications. By making an effort to bring together an ample network of proposers, we have identified representative European stakeholders in the subject, which will serve as the basis to organize the activities in a broader context within NANOCOHYBRI. We have designed a series of networking activities aiming at achieving impact among all stakeholders and successfully bring quantum coherent behaviour closer to society. We should note that many partners have met in the past in several conferences and training schools. Among these, the Vortex school series, organized every two years since 1998, is a major training event, which presents an overarching view of the subject and traditionally includes participants from related emerging subjects. Students participate eagerly in these schools and some have evolved into major present players in the field.

During NANOCOHYBRI, we will organize:

- Direct interactions among the different communities, aimed at achieving common results by fostering short-term scientific missions, STSMs, among participants.
- Major training schools during the first and third years.
- Three workshops on specific themes, each one targeted to address the needs of a work package.
- A general workshop and a conference during the end of third and fourth years.
- A Virtual Institute, to promote exchanging skills, infrastructure and experimental facilities.

In this way we will encourage concrete collaborative efforts. Each WG is involved in at least two workshops, one around the WGs theme and another one in collaboration with other WGs. European as well as non-European stakeholders gather in international meetings organized regularly. These include the European Conference for Applied Superconductivity (EUCAS) and other major meetings like Materials and Mechanisms of Superconductivity (M2S). The Action will coordinate the main activities with the organizers of these events, aimed at researchers from all over the world, promote sessions devoted to specific themes around the WGs of the Action and foster the participation of young scientists in these events.

We will also establish durable links with the growing business of superconductivity. We will build a group dedicated to industry and SME. Help identifying future opportunities for growth in the business of science (e.g. new systems able to provide stronger magnetic fields) and in solving the problems posed by the markets where superconductivity is expected to play a key role (e.g. new devices for robust quantum computation or provide better performing current carrying tapes by controlling pinning). We expect that two of the STSMs each year will involve secondments with industry.

II) DISSEMINATION AND/OR EXPLOITATION PLAN

The essence of the Action is to share knowledge, expertise and facilities around quantum coherent nanoscale hybrid devices. A key ingredient to achieve this goal is to transmit the information efficiently to all stakeholders. By increasing the awareness of each member's current line of research we hope to create a better collaborative and communal environment. Communication is also important to inform people outside of the action of the recent findings. In addition to the instruments provided by COST, we will work on the Virtual Institute on Coherent Nanoscale Hybrid Devices.

We will create a webpage centred around the Virtual Institute, with the aim to advertise skills and facilities to the largest possible extend and provide clear planning of forthcoming activities. Our meetings will be inclusive to all stakeholders, new directions of research, and industry. We will use each event to increase awareness about the Action among excellent European researchers outside the field, asking them to share their expertise and seeking for collaborations. Of course, we will make appropriate provision of Intellectual Property Rights following usual rules in EU projects whenever needed.

We also plan to reach out to the scientific community outside the action in order to maximize our impact. As usual in the field, we will publish in journals our work, and include every paper in open access platforms such as ArXiv. We will also issue one book covering the field from a pedagogical perspective with the aim to train the new generations of stakeholders. We will highlight publications made in common among participants in the Action. We will monitor such common publications and set a yearly goal for increasing the ratio of collaborative papers.

In all workshops, we will aim at maximizing industrial participation and discuss with them about our facilities and skills. The objective will be to promote technological transfer while being informed of the latest solutions that are available on the market for experimental scientists.

Finally, we plan to reach out to the general public including teenagers and freshman students. This will be done by issuing press releases, giving popular talks and by using social media such as LinkedIn and Twitter. We will have a section in the Virtual Institute dedicated to popularize our work.

C) POTENTIAL FOR INNOVATION VERSUS RISK LEVEL

I) POTENTIAL FOR SCIENTIFIC, TECHNOLOGICAL AND/OR SOCIOECONOMIC INNOVATION BREAKTHROUGHS

The innovative outcome of NANOCOHYBRI relies in putting together techniques and knowledge from different subfields in superconducting quantum technologies. Promoting meetings of disparate communities, often including different backgrounds, will produce synergies leading to innovation breakthroughs.

Dissipationless transport occurs because all Cooper pairs condense at a single energy level, protected from scattering by the presence of an energy gap. Dissipationless transport mostly leads to innovation in the electricity grid, medicine (high magnetic fields for magnetic imaging and accelerators) and transport of persons, often through large size machines and appliances based on current carrying conductors. The synergies sparked by NANOCOHYBRI will be varied. For example, stakeholders in, say, proximity induced superconductivity, usually do not meet stakeholders in large current carrying applications. However, there is a pressing need to understand pinning effects related to normal inclusions in tapes and current carrying devices. Knowing how superconductivity extends into the inclusions, either normal or ferromagnetic, is important to be able to design the pinning landscape. During the time frame of this Action, we will define and execute a challenging roadmap in order to obtain critical currents up to 2000 A through a 1 cm wide tape at 20 T and 4.2 K. These numbers can be achieved thanks to the positive impact of the collaborative efforts carried out within NANOCOHYBRI.

The first quantum revolution when applying quantum mechanics in the microscopic realm changed our lives by introduction of technological devices as transistors, light-emitting diodes, computer memory elements, lasers etc. The new Quantum technologies European flagship program will put Europe at the forefront of the second quantum revolution which will be based on the most fundamental principles of quantum mechanics like discreteness, coherence and entanglement. In particular, the flagship initiative is expected to turn Europe's excellent research results in areas including quantum sensing and quantum simulation into concrete technological opportunities that can be taken up by industry. The aim of NANOCOHYBRI is to support this initiative from the beginning. We can expect to considerably improve the control of quantum information in devices by using unconventional superconductors. Cross-cutting collaboration with scientists in the field of low dimensional superconductors will be instrumental to integrate these in hybrid devices and find new systems for quantum information.

3) IMPLEMENTATION

A) DESCRIPTION OF THE WORK PLAN

I) DESCRIPTION OF WORKING GROUPS

The Working Groups are organized following the scientific program. The list of topics, objectives and tasks is not exhaustive and will be open to the inclusion of new developments and opportunities, defined by the stakeholders of the Action.

WG1: Low-dimensional hybrid systems.

NANOCOHYBRI will join relevant stakeholders in low dimensional systems, including thin film deposition, interface superconductors and monolayer systems. In order to explore the fascinating properties of these ultimately thin materials we will combine different experimental tools. The growth and optimization of novel two-dimensional materials and/or interfaces will be done via chemical vapour deposition, ultra high vacuum molecular beam epitaxy or atomic layer deposition. We will fabricate ultimately thin systems—down to a single atomic layer—of deposits on Si. Other two dimensional (2D) materials, such as transition metal dichalcogenides (NbSe2, MoS2, MoSe2, WS2 and WSe2) will be obtained by exfoliation. This procedure is not scalable to wafer sizes but allows obtaining structurally almost ideal materials. The nature of these 2D materials, the characteristic energy and length scales of electron-phonon, spin-orbit and other interactions and correlations are crucial for their potential use in both nanoelectronics and spintronics.

We will also fabricate 2D based nanodevices, ranging from a Hall-Effect bar (HE) structure (with or without gate), a Transmission Line Measurement (TLM) structure, and a Top Gated-Field Effect Transistor (TG-FET) structure. These will be realized either in-situ, by using mechanical masks and capping, and in state-of-the-art clean room facilities equipped with all needed nanofabrication tools. Complex zero-dimensional nanocomposites will be obtained by cluster deposition.

At present we have a considerable control over the properties of disordered superconducting ultra-thin films, thanks to which one can cross from a superconductor into an insulator. The insulator as well as the superconductor bear interesting properties that lead to new superconducting behaviour. These address the fundamental problem of electronic correlations in presence of controlled disorder and can be used to improve high frequency applications of superconductors and particle detection.

We will explore extensively electronic properties of these systems using surface sensitive techniques, such as angle-resolved photoemission spectroscopy (ARPES), scanning tunnelling microscopy and spectroscopy (STM/STS) or micro-Raman microscopy, and quantum transport under very high magnetic fields. Ultrafast optical measurements will serve to study anharmonicity and its relation to high critical temperatures. We will explore phonon behaviour in confined systems using X-ray scattering experiments at European Synchrotron radiation facilities and develop new imaging techniques for electronic phase separation phenomena, such as X-ray holography. From the theoretical point of view the superconducting properties of these materials will be studied by Bogoliubov-de Gennes numerical simulations and ab-initio calculations.

The objectives of this WG will be:

O 1.1. To obtain improved critical temperature in low dimensions by modifying charging effects and confinement geometry.

O 1.2. To understand the relationship between the normal phase and unconventional superconductivity.

Tasks:

T 1.1. Fabricate, study and model interface superconductors consisting of monolayers, sandwiches, constrictions and materials with a pronounced two-dimensional character.

T 1.2. Fabricate, study and model hybrid structures combining superconducting with normal, ferromagnetic and semiconducting systems.

Milestones and deliverables:

M 1. Workshop on interface and monolayer superconductors (month 11).

D 8. Report on the main advances in the field on interface and monolayer superconductors, including the workshop and publications related to the WG1 of the Action (month 13).

WG2: Novel devices from hybrid interfaces.

NANOCOHYBRI includes experts in the fabrication of junctions, theoreticians that calculate the properties of the localized levels at the junctions and experimentalists able to tune and measure these levels. We will integrate materials where the Cooper pair wave function has a sign change into devices. An example is the two dimensional electron gas (2DEG) formed at the interface between insulating transition metal oxides $LaAlO_3$ and $SrTiO_3$ (LAO/STO). This system shows many interesting properties, including high-mobility, superconductivity and large tuneable spin-orbit coupling. Many theoretical papers predict the occurrence of unconventional pairing, but the properties of the superconducting state are still largely unexplored experimentally. The interfaces can be integrated in Josephson junctions and SQUID devices, appropriately patterned to design geometries where we can control the phase of the superconducting order parameter of LAO/STO.

We will map superconducting properties in devices using advanced microscopy tools. For example, we will measure a small junction in a flux geometry or with a gate that will make up the knob required to manipulate localized levels and study these, down to atomic scale. This will bring to day new length scales, closer to the Fermi wavelength, into the problem of hybrid superconductivity, and show novel ways of manipulating and coupling these states to the environment.

NANOCOHYBRI will also promote collaborations to understand circuits based on hybrid systems and how to improve their performance. For instance, the discrimination of heating versus phase slip phenomena is still very difficult in many small size systems, yet it is fundamental to improve resolution of the experiments and applications. We will also develop new photon detectors. The way the superconducting condensate acts on nanowires and other nanosized superconducting systems requires fine tuning of the trade-off between photon energy and wavelength (or spatial scale). For instance, THz single-photon detection is possible with quantum dot detectors and extreme THz confinement can be achieved in a microcavity laser based on a planar sub-wavelength resonant circuit.

We will study in detail superconductor/ferromagnet hybrids. For example, we will locally polarize the spins in the F layer by quantum units of flux moving on the S layer. This mutual coupling brings about a series of interesting phenomena such as the damping of flux motion and the associated generation of magnons, or the imprinting of the vortex flux steps into the ferromagnetic layer. In proximity systems with a magnetic metal having strong spin-orbit Rashba interaction, long range correlations have been observed, with rotations of the superconducting order parameter. We will image these correlations and use them to make new types of junctions, so called ϕ-junctions, of an arbitrary phase difference that depends on the magnetic moment.

Of great recent interest are hybrids between a superconductor and a topological insulator. Participants of the Action use nanowires of topological insulators to make Josephson junctions, focusing on the particularly interesting case of junctions hosting only a few modes. Additionally, we will explore hybrid systems consisting of a superconductor on top of a topological insulator using scanning probe techniques.

In this WG we will combine microscopic calculations of the bandstructure and of magnetism for a variety of different junctions together with direct measurements of the Josephson effect using low temperature, low noise and transport experiments. We will also use advanced microscopies (STM/STS, Magnetic force MFM, Squid on a tip) to study local properties in devices.

The objectives of this WG will be:

O 2.1. To provide new systems improving control of quantum circuits.

O 2.2. To improve photon detectors and bolometers.

O 2.3. To make phase sensitive experiments in Josephson junctions made of unconventional superconductors.

Tasks:

T 2.1. Find hybrid systems improving handling and read out of quantum information.

T 2.2. Nanopattern two-dimensional systems into junctions and study the Josephson current and the junction's properties.

Milestones and deliverables:

M 2. Workshop on superconducting junctions for detectors and quantum devices (Month 19).

D 9. Report on the main advances in the field on superconducting junctions for detectors and quantum devices, including the workshop and publications related to the WG2 of the Action. (month 19).

WG3: Hybrids with nanoscale vortex pinning and nanofabrication for high magnetic fields.

NANOCOHYBRI will join expertise in characterizing vortex behaviour in different topical superconducting systems, including cuprates, pnictides or MgB2, in nanopatterning pinning centers and in modelling current dynamics in superconductors.

We will explore vortex pinning and current transport in the range of liquid helium temperatures and at high magnetic fields. This remained unaddressed until very recently and is expected to considerably influence new applications. Within this network, we expect interesting synergies between applications and fundamental physics. For instance, the overdoped regime of the cuprates, such as REBa2Cu3O7-x, recently came into focus. Close to the quantum critical point (beyond the optimum Tc), different experiments show a sizeable increase of the pair condensation energy and possible vortex structure maximizing pinning energy. Within NANOCOHYBRI we will provide the combined approach of model, controlled fabrication, visualization at the nanoscale and current carrying tests, needed to engineer artificial pinning centres and obtain the desired critical current enhancement.

At the same time, we will consider manufacturing options that take into account costs, which have to remain affordable. Coated conductors provide a low cost chemical solution and growth. Supported by simulations and visualization of pinning centres and vortex positions, NANOCOHYBRI can considerably help in achieving this goal. Present efforts aim at the range of 20 €/kAm, reducing costs by a factor of five, as compared to the present status. This would enable a fast penetration into the market of machines for energy production or generation of high magnetic fields.

On the other hand, patterned thin films of superconducting materials offer new opportunities to control vortex pinning, obtaining model systems for fundamental studies, providing new devices and improving the properties of sensors based on superconductors.

In low Tc superconductors, advances in patterning allows creating smaller nanowires, unveiling new regimes of conduction, dominated by surface superconductivity and providing enhanced critical field with respect to larger sized wires. 2D patterned arrays provide a unique test-bed for a dynamic transition between a frozen vortex lattice pinned into the array and a moving lattice. The controlled fabrication of large arrays of equally sized pinning centres allows determining precisely critical exponents of vortex transitions through transport experiments (dynamic transitions) and through direct observation using advanced microscopies (order-disorder or pinning induced transitions). In high Tc superconductors, such as YBCO, patterning can take advantage of the strong dependence of its properties on the carrier concentration. We can expect a metal insulator transition by reducing the hole doping. By using a non-homogeneous electric field obtained by nano-engineering the doping level, we can aim at forming reconfigurable pinning potentials. Introducing ferroelectrica in periodic arrays, we can aim at modulating the pinning potential by controlling the electric field on top of the ferroelectrics and modify locally superconducting properties.

Concerning the methodology, in this WG, we will combine advanced simulation tools, using Ginzburg-Landau functional, electrical characterization to measure the critical current and advanced microscopy tools (such as Scanning Hall magnetometry, scanning SQUID microscopy, including SQUID on a tip microscopy and three-axis vector nanoSQUID, magnetic force microscopy, tunnelling microscopy and optical microscopies) combined with high resolution electron microscopy, to identify defects in the nanoengineered samples and measure positions of single vortices. We will investigate vortex pinning locally by low temperature magneto-optical imaging combined with electrical and heat transport. The Action will also bring new and promising techniques that are still under development to the next level, such as manipulation of individual vortices by injection of quasiparticles and local photon irradiation.

<u>The objectives of this WG will be:</u>

O 3.1. To control vortex pinning in superconductors by a combined approach of simulations, visualization critical current measurements and nanostructural strain characterization.

O 3.2. To enhance pinning by nanostructures in view of improving device applications.

O 3.3. To open new routes for dissipationless current transport using nanowires and patterned arrays of nanostructures.

<u>Tasks:</u>

T 3.1. Investigate vortex pinning energies in the overdoped regime for different nanostructured landscapes.

T 3.2. Study vortex motion in nanowires and in nanopatterned arrays.

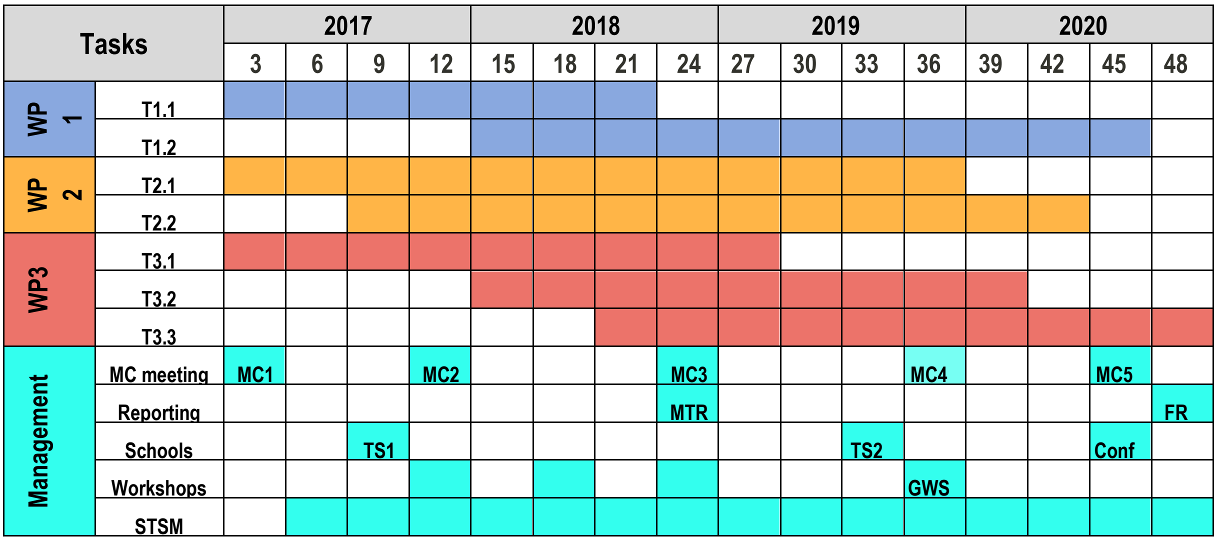
T 3.3. Design nanopattern electric field devices into superconductors.

<u>Milestones and deliverables:</u>

M 3. Workshop on vortex pinning (Month 25).

D10. Report on the main advances in the field on vortex pinning, including the workshop and publications related to the WG3 of the Action (month 25).

II) GANTT DIAGRAM



III) PERT CHART (OPTIONAL)

IV) RISK AND CONTINGENCY PLANS

We can identify risks in organizational activities and general collaborative objectives.

Risk	Likelihood	Involved structure	Impact	Contingency plan
New groups joining the Action have low or inexistent interactions.	M	MC	H	Identify potential for collaboration and integrate new members in the organization of meetings.
Partner leaves the Action.	L	MC	M	Reorganize tasks and planned meetings and seek for other participants holding similar skills.
WG act as independent entities.	L	MC, WGs	H	Integrate all WGs in the organization of a major training event or school.
It is difficult to make low dimensional systems with improved superconductivity.	M	WG1	L	Identify alternative methods and include experts of these into the Action.
Hybrid structures do not provide expected performance for sensors.	L	WG2	M	Modify methods to improve components of the hybrid structure. Discuss in a specific workshop with additional experts.
Modelling of vortex motion remains unrealistic with respect to actual behaviour in some current-carrying devices	H	WG3	M	Organize a dedicated workshop to make modelling more realistic. Consider calculation capabilities within the workshop and expand these if needed through collaborations.

L=low; M=medium; H=high

B) MANAGEMENT STRUCTURES AND PROCEDURES

NANOCOHYBRI will follow COST rules and procedures. The management system will embrace the vision and mission of COST, being European, open and inclusive, involve researchers from different disciplines, gender equal, engage young researchers and develop easy networking tools within simple rules. The Action will follow the "Rules for Participation and Implementation of COST Activities". The Action will be handled by a **Management Committee** (MC), with members nominated during the first weeks of the Action. The Memorandum of Understanding will serve as the basis for participation in the MC by countries that might join the Action during the first three years. The Action is aimed for a total duration of four years.

The **tasks of the MC** will be to:

- Organize the Action budget, making it possible to set-up up yearly activities aimed at achieving the goals of the Action. In particular:
  - Organize and foster **scientific exchanges** through short term scientific missions (STSM). The MC will guarantee that this exchange mechanism remains at the core of the Action and make sure that activities needed for a smooth development of the scientific objectives of the Action receive appropriate travel funding.
  - Decide on the main responsible persons for planned **training schools** and workshops and allocate the budget needed for the organization of these meetings.
- Guarantee and promote the participation of **early career researchers** in the Action.
- Monitor **gender equilibrium** within the program, analyse results and implement corrective measures to improve gender balance.
- Explore and inform participants about private initiatives for funding science or science dissemination activities (such as Axa, Volkswagen or BBVA foundations), with the aim to bring the subject of superconductivity closer to society.
- **Monitor and foster dissemination** activities for both, great public and for policy stakeholders.
- **Monitor the amount of publications** made in collaboration among stakeholders of the Action, analyse results and foster collaboration to improve the ratio of collaborative publications with respect to all publications of the Action.
- Organize collaboration with industry, fostering an active participation and monitoring the main results of the Action that are considered interesting for applications.
- Monitor the progress of the whole Action, by writing a midterm report and an annual report, highlighting work made in collaboration among participants and describing meetings (their initial goals, the development and the results achieved).

During the first weeks, we will announce NANOCOHYBRI through a preliminary webpage that will be distributed through emails, at conferences and workshops, at societies, through webpages of the network of proposers and through social media. The kick-off meeting will be held shortly after the Action is granted and will be used to appoint the Action Chair and Vice-Chair, the coordinators of the WGs, the responsible person for the STSMs and a first proposal for workshops and meetings, including their coordinators. The meeting will also be used to set-up gender equilibrium monitoring, decide a responsible person for the dissemination activities and a working group for collaboration with industry. **The WGs** will organize specific activities and their coordinators will be responsible for the development of the tasks and objectives and for reporting to the MC. In particular, the WGs will gather all the research activity carried out by the participants of the action and monitor about it in the webpage. The aim will be to coordinate efforts by establishing a complete list of ongoing research projects among participants, identifying common points and possible duplications and promoting networking activities to ensure collaborations. Each WG will have two coordinators (a main coordinator and a vice-coordinator) who will make the list and publicize it on the webpage. The WG leaders will also:

- Monitor and report to the MC the activities carried out by the participants (in particular publications).
- Foster contributions to the website by Action members (blog like postings on achievements).
- Foster STSMs within their respective area (making sure that, whenever possible, these lead to common publications).
- Actively promote gender equilibrium.
- Propose young researchers for invited talks within the meetings of the Action and in related conferences and meetings.

Furthermore, we will set-up a **group dedicated to industry and SME** relations. They will help organizing sessions dedicated to industry at each meeting, monitoring the activity of participants from industry and the collaborations with industry. The responsible person for **dissemination activities** will work closely with the Action Chair and Vice-Chair, establishing a definitive webpage during the first six months of the project and coordinating the inclusion of new content in it as well as the flow of internal information within the Action. Additional dissemination activities will be organized in collaboration with each WG leader. The aim will be to organize one dissemination activity to schools or the public within the context of each meeting organized within the Action. **Gender balance** will be addressed by yearly monitoring the male/female ratio in each participating country, clearly showing the result on the different career levels (PhD, postdoc, junior and senior tenured). The responsible person will report to the MC the results and suggest measures to improve gender equilibrium. NANOCOHYBRI aims at having gender equilibrium in the Chair-Vice Chair and in the WG leadership structures. **Participation of young researchers (ECI)** will be natural in the training activities of the Action. All scientists involved in the network of proposers have organized conferences or meetings in which early stage researchers were involved at a high level and had a significant allocated time. In addition, the Action aims at including ECIs in each one of the WG as main or secondary responsible persons. In collaboration with the dissemination activities, the Action will appoint an ECI to actively promote the Action in social media.

We will embed the Action within a **European Virtual Institute** that will include a list of available facilities and expertise. We will benefit from ongoing examples that have been working successfully during past three years in related topics. The value of this tool is well proven—it considerably fosters networking by inviting everybody to list their skills and infrastructure, it improves training by giving young researchers information about who is who in the network which they can check on their own and is helpful in avoiding duplication. The Institute will be mentioned in posts about publications of the Action and in the dissemination activities. It will help publicize the action to industrial stakeholders and the society as a whole.

The Management activities will lead to the following deliverables:

D1, D2. Midterm and final reports of the action, including the main scientific achievements and monitored activities of the management committee.

D3, D4, D5, D6, D7, D11, D12. Reports after each Management Committee meeting (five reports), including activities performed during the relevant period of the action: meetings, an account of scientific advances in technical WGs, including publications and a report monitoring activities of management committee and (STSM, ECI, gender equilibrium, dissemination, industry and SEM and a virtual institute).

C) NETWORK AS A WHOLE

The commitment of a large community of researchers to the Action is made visible through the network of proposers, together with the previous networking actions in related fields. The network includes 45 proposers from 18 COST member countries and is:

- **Committed to support excellence.** The network supports very active scientists in the fields of vortex physics and current transport, two-dimensional systems, sensors and high Tc superconductivity. The proponents are distributed in experiments and device fabrication (60%), theory and simulations (25%) and industrial applications (15%). The participants routinely use advanced infrastructure, consisting of nanofabrication facilities, large or medium-scale experimental facilities (high magnetic fields, neutron, synchrotron, high resolution transmission electron microscopies) and computational facilities, whose access is usually granted on a competitive basis. At the national level, each country includes a participant that holds a major competitive national grant and relevant prizes and recognitions. The participation is balanced among the main objectives of the proposal, with approximately one third of the participants in each workgroup. There are 7 ERC grantees involved in the project, three of which are Starting grants. The ERC grantees concentrate their efforts in relevant aspects of the Action, including devices, current carrying systems, high Tc superconductivity and interfaces.

- **Engaged in fostering European leadership.** Traditionally, the participants have lead some of the most relevant efforts in the field, including multigap superconductivity, pinning by nanostructures or the development of hybrid ferromagnetic-superconducting systems. These efforts are managed and put within the international context through connections with non-European colleagues through meetings and collaborations. Similar coordinated efforts are ongoing in the US, Japan and China.

- **Inclusive to all researchers.** Nearly 30% of the network consists of inclusiveness target countries. The participation includes theory and experiment, at least in two cases with advanced nanofabrication and measurement equipment that has been funded through EU calls. Traditionally, the proposers have been opened to the inclusion of researchers in other fields by maintaining regular contacts. Often, when the proponents have been organizers of meetings, they have invited experts in related fields, such as fluid dynamics and colloids, disordered systems, Bose-Einstein condensation and cold atomic gases, advanced electron microscopies, detector applications, graphene and quantum computation. COST near neighbour countries as for instance Russia and Ukraine are well integrated within the activities of the proponents, with numerous ongoing collaborations and exchanges.

- **Engaged in fostering the participation of young researchers and improving gender equilibrium.** The network includes 8 early career investigators and about 20% of female participants. There is a large push by the young generation, supported by a cohort of senior researchers working in the field. In the meetings now organized within the field, more than 20% of invited talks are usually given to early career investigators and often include additionally PhD students. On the other hand, the management structure will aim towards improving gender equilibrium in the main organizational activities of the network. Recognizing the gender gap in the field, monitoring its development and circulating the results are important tools. But these need to be backed up by a large female involvement in the main positions of the Action.

- **Fostering applications and collaboration with European infrastructures, industry and other stakeholders.** The network includes a representation of large and small size companies. Members of the network of proponents routinely collaborate with many companies within specific EU programs. These include all the way from fostering small “garage” size spin off companies up to efforts held within large companies. Companies actively participate in the development of power electronics (current carrying applications, such as tapes), construction and design of high magnetic field coils, microscopy and new sensors based on superconducting devices. Companies will provide an additional dimension to better explain to society and policy the relevance of the results achieved during the Action. Furthermore, many of the proponents are routine users of large scale facilities included in the European Research Infrastructure Roadmap ESRFI, such as high magnetic field, neutron and synchrotron radiation facilities, and naturally will include stakeholders from facilities.