Brussels, 13 April 2018

COST 024/18

DECISION

Subject: **Memorandum of Understanding for the implementation of the COST Action "Trapped Ions: Progress in classical and quantum applications" (TIPICQA) CA17113**

The COST Member Countries and/or the COST Cooperating State will find attached the Memorandum of Understanding for the COST Action Trapped Ions: Progress in classical and quantum applications approved by the Committee of Senior Officials through written procedure on 13 April 2018.

MEMORANDUM OF UNDERSTANDING

For the implementation of a COST Action designated as

COST Action CA17113
TRAPPED IONS: PROGRESS IN CLASSICAL AND QUANTUM APPLICATIONS (TIPICQA)

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 REV2);
b. “COST Action Proposal Submission, Evaluation, Selection and Approval” (COST 133/14 REV);
c. “COST Action Management, Monitoring and Final Assessment” (COST 134/14 REV2);
d. “COST International Cooperation and Specific Organisations Participation” (COST 135/14 REV).

The main aim and objective of the Action is to provide a platform to develop new tools, technologies and ideas for classical and quantum technologies with trapped ions, foster transfer of mature technologies to socioeconomic partners. Specifically, this Action targets to overcome current limits in the field of trapped ions on quantum control, scalability, precision measurements, and hybrid quantum systems. 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 80 million in 2017.

The MoU will enter into force once at least seven (7) 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 REV2.

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 REV2.

TECHNICAL ANNEX

OVERVIEW

Summary

In recent years, ion traps have developed from a topic of fundamental research into a versatile tool for a wide range of research topics and quantum technologies. With the ability to isolate the ions from their environment, atomic and molecular ions can now be studied in unparalleled detail. This capability has led to important scientific progress in fundamental research, such as the measurement of cold collisions between trapped ions and cold atomic or molecular particles, the study of the interaction of light with trapped ions, or mass measurements with ultra-high precision. Beyond purely fundamental research, ion traps have become indispensable for many applications and technologies. Trapped ions are currently the most promising implementation of quantum information processing devices where many essential building blocks have been developed in recent years; magnetic field sensing with high sensitivity has been demonstrated and some of today's best atomic clocks are based on atomic ions. These applications have the potential to revolutionise many aspects of our daily life. The aim of this Action is to enhance the current applications of trapped ions by supporting Europe-wide collaborations and knowledge exchange, and to allow these technologies to be taken a step further towards their commercialisation.

Areas of Expertise Relevant for the Action	Keywords
● Physical Sciences: Atomic, molecular and chemical physics ● Physical Sciences: Ultra-cold atoms and molecules ● Chemical sciences: Chemical reactions: mechanisms, dynamics, kinetics and catalytic reactions ● Computer and Information Sciences: Quantum information processing	● ion trap ● metrology and fundamental constants ● ultra-high resolution spectroscopy ● quantum information and hybrid quantum systems ● cold molecules and ion-neutral interactions

Specific Objectives

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

Research Coordination

● Coordination of ion trapping research within Europe, in particular on
- large-scale entanglement, with the goal to entangle more than 50 ions, enabling quantum systems with capabilities beyond classical computers.
- robust atomic clocks based on trapped ions, which merge very high performances with a compact and transportable design.

● Coordination of ion trapping research within Europe on, in particular on
- development of micro-fabricated traps with reduced heating rates to facilitate integration and scalability, and prepare the ground for tomorrow's quantum computer.
- novel interrogation protocols for robust and decoherence-free applications.
- creating quantum networks by coupling ions to other quantum systems.

● Organizing meetings, training activities, and STSMs to foster information exchange and collaboration.

● Advancing ion trap technology for commercialisation with socioeconomic partners.

● Promoting new applications of trapped ions in physics, chemistry, bio- and nano-sciences.

● Creating a database for computer codes to simulate the dynamics of trapped ions and their interactions with electro-magnetic fields.

● Creating a database for a "universal" optimised tool kit for ion trap experiments including e.g. important details on materials (outgassing, UHV electronics, etc.).

● Dissemination of research results to scientific community and general public.

Capacity Building

- Coordinate and organise regular Europe-wide training activities for PhD students and ECI to facilitate fast research progress.
- Provide opportunities for knowledge and technology exchange between research groups of the Action, and between research groups and socioeconomic partners.
- Encourage transfer of know-how and emergence of new research projects through mobility (e.g. through STSMs).
- Providing a platform for the stakeholders and socioeconomic partners to interact with each other and devise a common roadmap.
- Bridging the disciplines of Physics, Metrology, Chemistry, Mathematics, and Information Technology and exploit the multi- and interdisciplinary potential of the community.

TECHNICAL ANNEX

1. S&T EXCELLENCE

1.1. CHALLENGE

1.1.1. DESCRIPTION OF THE CHALLENGE (MAIN AIM)

Ion trapping has many **applications** across science and technology. Along with constant progress **in high precision mass spectrometry** (which is well developed and widely employed in research and industry), emerging technologies such as **quantum information processing**, **quantum sensing** and **optical atomic clocks** will have a major economic impact in the next decade. It is widely accepted that ion traps have a vast potential for the implementation of new quantum technologies, which is strongly emphasized by the upcoming European Quantum Technologies Flagship and several national programmes throughout Europe (i.e. UK, CH, D). The Quantum Technologies Flagship will consist of focused FET-like projects, which will be given to the most successful teams, whereas many smaller groups might not receive comparable funding. Thus, **a coordinated multidisciplinary European approach is strategically important since it forms a critical mass of groups and partners, and combines the individual efforts within and outside quantum technologies.**

This COST Action will provide a platform to develop new tools, technologies and ideas for classical and quantum technologies based on trapped charged particles, to foster rapid scientific progress and transfer of mature technologies to socioeconomic partners. Specifically, **this Action targets to overcome the current limits in the field of trapped ions** in terms of

- quantum control,
- scalability,
- precision measurements, and
- hybrid quantum systems.

This will immediately lead to breakthroughs in science and would provide numerous innovative applications in quantum information processing, metrology and sensing.

The involved **community consist of many research groups of relatively small size** (with an average size of 7 members including PhD students), **which renders cooperation vital in order to facilitate continual fast progress**. Across research areas that utilise trapped ions, key-technologies, tools and protocols are usually developed by each research group individually. A highly dynamic network is fundamental to ensure an efficient **exchange of know-how and technologies** between stakeholders and thus facilitates rapid progress not only in research but also in emerging technologies. This has potentially a **significant long-term socio-economic impact, which the Action aims to strengthen through active involvement of private sector partners**.

Moreover, the **basic and advanced training of PhD students and Early Career Investigators (ECI)** is currently pursued separately in each research group, which significantly burdens smaller research groups. With network-wide training events, a significant part of capacity building measures can be more effectively implemented. Furthermore, network training events additionally facilitate the exchange of novel ideas, know-how and technologies between stakeholders, and will **train tomorrow's experts in the domain**.

The ion trapping community is structured along COST's main characteristics of openness and inclusiveness with existing partners **from several COST Inclusiveness Target Countries.** This Action

Funded by the Horizon 2020 Framework Programme
of the European Union

will strengthen these links and give a platform for collaboration, in particular for ECI from less research intensive countries.

A considerable impact will be made by the **encouragement of mobility through STSMs and education of early-career investigators**. They will be able to profit from this network by acquiring excellent training and introduction to polyvalent approaches in various disciplines. The Action will therefore enable researchers to establish scientific contacts and network opportunities early in their career and will thus foster the integration of the European research community.

This Action will provide an **efficient network for ion trapping research groups by integrating all European ion trapping groups and relevant international partners**, with a **special focus towards ECI training, inclusion of less-research intensive countries, and involvement of socio-economic partners**. A close collaboration throughout the network will allow tackling the challenges of classical and quantum technologies based on trapped charged particles. The joined effort will help to develop and implement advanced precision devices for research and industry.

1.1.2. RELEVANCE AND TIMELINESS

Trapped ions have recently evolved into one of the most active fields of scientific research, offering important **prospects for socioeconomic** relevant **applications** such as **quantum computation, quantum sensing and ultrastable clocks**. With an average of about 20 publications monthly, a regular newsletter, and a bi-annual European conference, Europe has currently a leading role in many ion-trap related areas. To maintain and strengthen Europe's key position, intensive collaboration between all groups is required.

Ion traps already have important economic applications such as **high precision mass spectrometry for chemical analysis**. In addition, quantum technologies have recently advanced from fundamental research into a stage where commercialisation can be considered. Atomic clocks based on trapped atomic ions are currently among the best frequency standards. These systems will most likely replace the current SI definition of the second by the cesium hyperfine transition. In fact, recently, the International Committee for Weight and Measures (CIPM) has recommended the Hg^+, Yb^+, and Sr^+ single-ion clock together with the Sr lattice clock as the so-called "secondary representations of the second". The **relevance and timeliness** of these high-precision applications of trapped ions was recently **highlighted by the Nobel Prize** for Physics **to David Wineland** (2012).

Currently, the UK is investing strongly into quantum technologies by creating Quantum Technology Hubs. Other countries, like Switzerland and Austria also strongly support research in this field. Most noticeably, the upcoming **European Quantum Technologies Flagship programme emphasizes the importance of quantum technologies** for European science and technology. As quantum technologies are tomorrow's solutions, it is important today to encourage scientific progress in this area and to strengthen the technology transfer of mature technologies from academia to industry.

This Action is the perfect breeding ground for the **development of research consortia** to give fertile and successful input **for the flagship initiative, other EU projects (i.e. FET) or national calls**.

Exchanging know-how, ideas and technologies will not only facilitate rapid progress in research but will also have significant economic impact. Due to increased competition, in particular from research groups in the US, Japan and China, rapid progress in Europe is essential to maintain and strengthen its leading scientific role in this field. Quantum sensors and devices have reached a level of maturation, which allows further exploitation. New research findings will open the way to commercialisation, which **will ensure that the European economy** also **benefits**.

1.2. OBJECTIVES

1.2.1. RESEARCH COORDINATION OBJECTIVES

This Action will strengthen the leading role of Europe in the field of ion trap related science and technologies by organising a Europe-wide, multidisciplinary joint effort to develop universal tools, technologies and theoretical methods for the trapping and manipulation of cold ions. It will focus on overcoming the current limits in quantum control, scalability of ion traps, precision measurements, and novel communication protocols between ion traps. The fields of quantum information, metrology and quantum networks will directly profit from this Action. In particular, the **SMART research objectives** are the basic building blocks of tomorrow's large-scale quantum computing, high precision clocks and high precision quantum sensors, such as:

- **Large-scale entanglement**, with the goal to entangle more than 50 ions, enabling quantum systems with capabilities beyond classical computers.
- **Robust atomic clocks based on trapped ions,** which merge very high performances with a compact and transportable design.
- The **development of micro-fabricated traps** with reduced heating rates to facilitate integration and scalability, and prepare the ground for tomorrow's quantum computer.
- **Novel interrogation protocols** for robust and decoherence-free applications.
- Creating quantum networks by **coupling ions to other quantum systems**.

The **SMART operational objectives** are:

- **Coordination of ion trapping research** within Europe.
- Formation of **four work groups** on specialized topics (quantum control, sensors and precision measurements, hybrid systems, ion trap tools & design).
- **Organizing meetings, training activities, and STSMs** to foster information exchange and collaboration.
- Advancing ion trap technology for **commercialisation** with socioeconomic partners.
- Promoting **new applications** of trapped ions in **physics, chemistry, bio- and nano-sciences**.
- Creating a **database for computer codes** to simulate the dynamics of trapped ions and their interactions with electro-magnetic fields.
- Creating a **database for** a "universal" **optimised tool kit for ion trap experiments** including e.g. important details on materials (outgassing, UHV electronics, etc.).
- **Dissemination of research results** to scientific community and general public.

1.2.2. CAPACITY-BUILDING OBJECTIVES

The COST Action will build a critical mass of European researchers to drive scientific progress. Fostering the **training of researchers, in particular Early Career Investigators**, in the area of trapped ions is of crucial importance for the continued future success of the field in Europe. So far, for the individual groups this training is a significant effort, which slows down the progress of research activities, but is a necessary prerequisite for its future success in academia and industry. Furthermore, not all groups, in particular those from less research intense countries, have access to the latest technology and best training facilities. This COST Action aims to provide a conduit for efficient interaction, networking, exchange and education of (younger) researchers. This is highly beneficial for their own career development, while it is also important for the exchange of ideas, tools and technologies between the groups of this COST Action.

The **specific capacity building objectives** are:

- Coordinate and organise regular Europe-wide **training activities for PhD students and ECI** to facilitate fast research progress.
- Provide **opportunities for knowledge and technology exchange** between research groups of the Action, and between research groups and socioeconomic partners.
- Encourage **transfer of know-how** and emergence of new research projects **through mobility** (e.g. through **STSMs**).
- Providing a **platform for the stakeholders and socioeconomic partners** to interact with each other and devise a common roadmap.
- **Bridging** the **disciplines** of Physics, Metrology, Chemistry, Mathematics, and Information Technology and exploit the **multi- and interdisciplinary potential** of the community.

These objectives will not only facilitate the knowledge exchange between the research groups and provide high level of training but will also contribute to the European efforts to **develop highly skilled professionals for academia and industry**.

1.3. PROGRESS BEYOND THE STATE-OF-THE-ART AND INNOVATION POTENTIAL

1.3.1. DESCRIPTION OF THE STATE-OF-THE-ART

Trapped ions are versatile tools for a wide range of research activities. The excellent degree of control in the manipulation of trapped ions renders them one of the most promising emerging technologies for **sensing and high-precision applications**. For instance, single trapped ions have recently become a leading system for precision frequency measurements. Frequency measurements with fractional uncertainties on the order of 10^{-18} have been demonstrated, which makes them the most precise measurements in the world. These achievements have been recognised with the Nobel Prize Award in Physics 2012 to David Wineland. This highly advanced clock technology paves the way for innovations like improved satellite navigation systems and precision geodesy. Employing high precision measurements of the ion motion in the trapping potential, the masses of a range of charged particles have been measured with unparalleled accuracy.

The excellent isolation of the trapped ions from the environment makes them also prime candidates for **quantum information processing and simulations**. Single and two qubit gates have been demonstrated with fidelities beyond 99.9%. Various entangled states, such as Bell states and Schrödinger cat states of trapped ions have been created. Recently, entanglement of 14-qubit has been demonstrated. Multi-qubit quantum gates have been experimentally achieved and some quantum algorithms, such as quantum teleportation, error correction, and Shor's factorisation algorithm have been implemented. Scalability of the systems with respect to ion number, laser beams and physical size are at the heart of future research.

The ability to control, cool and detect ions also led to a range of novel **hybrid systems**, where the trapped ions are coupled to other quantum systems. Here, the atomic or molecular ions are interacting with other quantum systems such as gases of neutral atoms or molecules, electrons, positrons, quantum dots, radiofrequency strip-line cavities, or optical cavities. As shown in an ongoing Marie Curie Initial Training Network (ITN), several landmark studies have highlighted the potential for sympathetic cooling of molecular ions and for studying inelastic collisions and chemical processes at very low temperatures.

Ion traps also serve as extremely high-precision measurements in advanced **mass spectrometry**, where today's world records in precision are regularly achieved by European groups. Exotic or rare ions in traps push the frontiers of knowledge in this domain, in particular for antimatter experiments, which rely on charged particle traps.

1.3.2. PROGRESS BEYOND THE STATE-OF-THE-ART

The COST Action aims to make significant progress beyond the current state of the art as described above. The Action will overcome the current limits of quantum control, scalability, precision measurements, and connectivity of ion traps. This will directly boost progress in applications for quantum information, metrology and sensing.

One of the major objectives will be pushing the limits of **precision spectroscopy and sensing and extending it** to new systems like molecular ions and highly charged atomic ions. These offer prospects for accessing new wavelength regimes and facilitate the development of new types of clocks with enhanced sensitivities for e.g., the electron's electric dipole moment and time variation of fundamental constants. These developments will also pave the way for measurements of atomic and molecular properties such as electrostatic moments, polarizabilities and molecular structure with a vastly improved accuracy for the benefit of chemistry and AMO physics.

In the field of **quantum control,** the Action will aim at improving the gate fidelity and speeding up the gate operations, necessary to fully exploit the potential of quantum computing. One can typically implement gates in decoherence free subspaces in order to minimise the environmental noise. The gate operation can be quickened by optimising external control fields. Optimal control can be used to decrease the susceptibility of the gates to environmental noise. Entanglement is crucially for multi-qubit quantum gates. However, the larger the number of the qubits, the shorter the coherence time and the longer the creation process. One fundamental challenge is to establish multi-qubit entanglement that is robust against environmental noise. Moreover, the community explores the application of multi-qubit entanglement in the study of quantum simulation. Also, optimal control techniques can be used to identify robust computational subspaces for the implementation of fast and high fidelity two qubit gate operations. While the principle of quantum computers has been demonstrated with small ion crystals, currently activities focus on building a scalable quantum computer with trapped ions. This can be potentially realised by using a micro fabricated trap, or other **advanced trap architectures**, with designated trapping regions for quantum memory, computation and information transfer within the same trapping structure. Similar ion trap structures can also be employed to advance quantum simulation experiments. Together with designed interactions between qubits, this facilitates the simulation of exotic quantum systems on a larger scale. Trapped ions in Penning traps and trapped Rydberg ions are alternative candidates for the future.

Coupling trapped ions to other quantum systems such as neutral atoms, molecules or photons is another topic of this COST Action. This can have direct applications in terms of improved quantum memory or in establishing quantum networks. Furthermore, elastic collisions between ions and ultracold atoms are of interest for sympathetic cooling of the external and internal degrees of freedom of molecular ions. An important goal of the field for the future would be controlling collisions between atoms and ions e.g. with the help of Feshbach resonances or shape resonances. As already mentioned, an additional big challenge is the realisation of scalable designs for networks of ions in separated optical cavities, communicating with each other via photon exchange. These modular connections, representing a quantum version of the internet, could allow the connection of ion-based quantum computers through a quantum channels. Moreover, achieving strong ion-photon coupling in cavities could lead to the realisation of new schemes for ion entanglement. Alternatively to this route, strong coupling between ions and electromagnetic radiation could be accomplished for instance by coupling the ions with the evanescent wave created by a nanofiber passing at the centre of a Paul trap. These highly ambitious goals necessitate a strong collaboration between the different groups, to devise better and more reliable designs of ion-cavity hybrid systems.

1.3.3. INNOVATION IN TACKLING THE CHALLENGE

Innovative approaches in research will allow tackling today's questions in this area of research and technology. Trapping of charged particles has been known for over 50 years, and has greatly benefitted from technical progress made, in particular, the development of laser sources. Today, one of the main challenges lies in the scalability of systems. The multitude of original and novel approaches (e.g. microfabrication techniques, integration of optical and other components into the trap structure, ultra-narrow laser sources, low noise electronics etc.) were instrumental for the rapid progress.

The present Action is constructed in a very open way, with a multitude of contacts to other communities, in particular chemistry, biochemistry and nanosciences, to facilitate new and different approaches and innovative ideas, and to unleash the interdisciplinary potential which provides additional gain in the interplay of topics.

An important aspect of this Action is the transfer of mature technologies from the lab to the industry by actively seeking connections between stakeholders from academia and industry. A competence database as well as dedicated events will allow the implementation of privileged links.

1.4. ADDED VALUE OF NETWORKING

1.4.1. IN RELATION TO THE CHALLENGE

While direct research funding is indispensable for the progress of research activities and the translation of research developments into products, the exchange of technology, know-how and skills is vital for fast progress in research. The scientific community involved in this Action is very active in obtaining National and EU funding for individual research projects. The COST Action aims to provide a conduit to facilitate the rapid exchange of ideas, technologies and skills and to increase the number of bi- and multinational research.

The Action aims to lift some of the basic training of ECI and PhD students off individual research groups and provide networking opportunities, through networking events and exchange programmes. This will enable research groups to focus better on their core research programme. Through this, the Action aims to maintain and strengthen the currently leading role of Europe in many ion trap related research areas. In the long term, this will have a potentially major economic impact. The strength of this Action is its openness towards new ideas, new groups and participants and, at the same time, making a particular effort for a balanced participation with respect to geography, age or gender.

All European groups working with trapped charged particles are highly interested in joining this Action, as well as a large fraction of our colleagues from outside Europe, who intend to become international partners. Among the interested partners are also some of the major companies developing quantum technologies.

1.4.2. IN RELATION TO EXISTING EFFORTS AT EUROPEAN AND/OR INTERNATIONAL LEVEL

There are strong national research programmes to support ion trap related research, for example in Germany, Austria and in the UK. The UK's Quantum Technology Programme in particular has a strong ion trap related component. One of the British Quantum Technology Hubs is focused on the implementation of a quantum network based on trapped ions. Another Quantum Technology Hub is employing trapped ions to build portable magnetic field sensors and atomic clocks. While there is strong support for research in some European countries, funding levels in other countries are low.

This difference in research funding leads to an inefficient utilisation of talent and skills for the progress of ion trap related research and technology across Europe. This COST Action aims to mitigate the effects of varying research funding levels across the Action's member states by increasing the number of applications for EU or bi-national funding. By facilitating the exchange of skills, know-how and technologies, groups in COST Inclusiveness Target Countries will have access to new technologies and know-how while other groups have access to a wider pool of skilled researchers.

In the field of ion traps Europe faces strong competition from the USA. For example, there are several Multidisciplinary University Research Initiatives (MURI) e.g. on "Ultracold Molecular Ion Reactions" and on "Hybrid Quantum Optical Circuits" which have direct overlap with the research of this new Action.

Today, no other funded project exists to provide this essential network. There is a previous COST Action in which the participating community has built up strong ties within itself and ion trap research has tremendously gained in momentum. This new COST Action will help to respond to the new challenges and to allow for further rapid progress.

Most international research groups in the field have expressed strong interest to be International Partner Countries in this Action.The network of proposers reflects already the wide cross section of the Action. As indicated before, the network activities will be open to all, in order to form a large, inclusive community.

2. IMPACT

2.1. EXPECTED IMPACT

2.1.1. SHORT-TERM AND LONG-TERM SCIENTIFIC, TECHNOLOGICAL, AND/OR SOCIOECONOMIC IMPACTS

The wider ion trapping community has already demonstrated its high potential to link research and innovation. This had an increasing impact on science and industry (e.g. mass spectrometry). The recent developments of ion trap science in the quantum regime clearly indicate another boost of developments in the near future.

In the **short term, the impact** in science and industry will significantly increase the speed of research progress which facilitates the deployment of ion trap technologies for a wide range of topics. Examples are the utilisation of techniques from quantum information processing in high resolution spectroscopy of atomic and molecular ions, the investigation of the bio-molecular structures in trapped ionic molecules and the combination of trapped ions with cold atoms. Through this COST Action further applications in a wide range of topics are expected such as the development of cooling, interrogation and preparation methods for molecular species and hybrid systems.

The **long term scientific impact** is likely to be dominated by quantum simulation/ computation. Once established these achievements will be a global game changer as they allow for completely novel ways to conduct research.

On the side of **technological impact** the Action expects important progress with respect to

- micro-fabrication of traps, as they are the fundamental ingredient to almost all experimental applications, integration of optical and/or electromagnetic devices into micro-fabricated traps, allowing the development of tomorrow's quantum devices,
- the development and production of specialised electronics for ion trapping and
- the development of advanced lasers for ion trapping.

The expected **socioeconomic impact** will be manifold:

- Ultrasensitive sensors based on trapped ions are already important tools in our society, e.g. mass spectrometers for trace analysis of chemical compounds such as explosives or trace gasses in the atmosphere. These applications are essential for security and environmental research. They will be boosted along future developments of ion trap technologies.
- It is well known, that our modern society is strongly dependent on progress in high tech. For example, ultraprecise atomic clocks are essential for fast communication and GPS, but also for gravitational sensing applications.
- It has become clear that quantum technologies will have a large impact on our society (see e.g. quantum manifesto). As an example, quantum cryptography and quantum networks will lead to a safe communication. A quantum computer will have strong impact onto our society as it will allow for solving complex numerical problems that where not tractable before. Beyond direct applications of a quantum computer in science there will also be applications in meteorology and the trade market.
- In this COST Action the partners aim to closely liaise with industry to develop new products, which will promote European high tech companies. Several companies are already involved in ion trap based technology development and this Action will enhance their involvement.
- An important aspect of scientific research is the training and exchange of researchers between research groups. Highly trained professionals are essential for the economic success of the EU's high-tech industry. In addition, governmental and non-governmental organisations require experts for the development of tomorrow's quantum sensors. Through an exchange programme, training and networking events this COST Action will promote especially less research intense countries.

2.2. MEASURES TO MAXIMISE IMPACT

2.2.1. PLAN FOR INVOLVING THE MOST RELEVANT STAKEHOLDERS

The Action has been designed to involve all relevant stakeholders. The Action will maximise the involvement of the various groups and partners to ensure that the Action's objectives are met. The large majority of academic research groups from Europe will actively participate in the Action. At the proposal stage, this includes a large variety of groups from 2 to 80 members, from about 20 different COST countries, and with a large fraction of junior group leaders. The network meets the COST inclusiveness policy as groups from COST Inclusiveness Target Countries will be actively involved in this Action and it is aimed to organize at least one international conference in a COST Inclusiveness Target Country. Almost all researchers in the field from outside Europe are strongly linked to the Action, and will be participating in all events and STSMs. Dissemination is guaranteed to all stakeholders by a monthly newsletter (see next subsection) which is widely distributed to the community. The organisation of regular scientific schools and training events is dedicated specifically to attract and interest early career investigators. These young researchers, as well as colleagues from COST Inclusiveness Target Countries, are also the priority target group for Short-Term Scientific Missions, to allow a maximum level of interaction and exchange. A special measure will be taken to ensure gender balance: The Action will involve women at all levels in the programme, ranging from the participation of female ECI in all events, to the distribution of invited speakers, and the appointment of governance and WG leaders in the Action. Family-friendly STSM and the possible organisation of child-care at meetings will in particular support scientists of both genders with smaller children, to attend non-local events.

Neighbouring scientific domains (chemistry, aeronomy, biology, nanoscience) rely on ion trapping development and techniques and improved performance of these approaches will have a positive impact on these applications. As discussed before, a number of socio-economic partners are involved in the Action. There is already industry interest in ion trap based technologies and this Action aims to increase and deepen this (see next subsection) through networking and show case events for industry. In addition, commercialisation and entrepreneurship will be supported in this Action through tailored training events.

2.2.2. DISSEMINATION AND/OR EXPLOITATION PLAN

Communication and distribution of information as well as exploitation of results are fundamental pillars for the success of the Action. A variety of communication and distribution channels will be employed to maximise the impact. Internal dissemination will focus on the exchange of information between research groups and researchers in order to optimise interaction and to create added value, while external dissemination will showcase the work of the Action as well as inform a wider audience about the Action's activities. Exploitation of the Action's activities will benefit European high-tech companies.

The Action's **internal dissemination strategy** rests on four pillars:

a) Exchange of knowledge and expertise during workshops and workgroup meetings will facilitate the adoption of existing technologies, techniques and methods across the Action and helps to foster collaborations between the participating groups. The workshops and workgroup meetings will be promoted also among International Partners and non-members of the Action in order to facilitate interdisciplinary research and introduction of novel techniques.

b) Results achieved of the Action's activities will be published in the scientific literature and presented at national, European and international conferences.

c) Training schools organised in conjunction with the Action's workshops are aimed at training students and postdoctoral researchers in the basic and advanced techniques in ion trapping. The school's taught material will be made accessible across the Action to ensure the benefit for all members.

d) The Action's website will form an integral part of the dissemination strategy. It will contain a newsgroup, an internal knowledge database and a job market, thereby serving as an information portal for all members.

Different target groups have been identified and will be addressed in various ways **by the external dissemination plan**:

a) Scientists from outside the Action: As demonstrated in the last years, the ion trapper community is aware that real breakthroughs are often initiated by interactions with colleagues from different fields. The Action will pursue an active strategy of a very open Action by promoting multidisciplinary contacts at all levels and by encouraging dialogue with the wider scientific community. This will be realised by inviting colleagues from different fields to give keynote talks during the Action's meetings and by announcing all events beyond the Action. The publication of a bi-annual volume on advances in ion trapping will be an important tool for the community but also towards creating external interests and awareness. Naturally, the dissemination of concrete research results arising from the collaborative work nurtured through the Action will be assured through common publications.

b) Socioeconomic partners: This Action is determined to involve a larger number of socioeconomic partners, to increase the number of collaborations and to foster the emergence of novel applications. In addition to the strengthening of direct contacts with companies, the Action will set-up a competence database of all research groups involved in the Action, to demonstrate the existing scientific and technical expertise and to facilitate the search for new partners. Dedicated networking events with socio-economic partners will help to increase communications and interactions.

c) Society: The Action's website will also promote the activities and results to the wider public. The Action will make every effort to communicate the results through to public engagement, with the goal of improving the understanding of quantum devices within society. Outreach activities organised by the members of the Action such as public lectures, talks, open lab days and publicising in popular-science publications will be used for disseminating the results to the general public. The Action will organise the exchange of ideas and material for outreach activities to take advantage of the existing experience across the Action members.

Impact will be continuously monitored throughout the Action. It will be a standing Management Committee meeting item. The assessment of ongoing or terminated projects is a critical tool for the evaluation of the Action progress and will serve to identify novel or emerging fields. An impact analysis will be carried out, with respect to all target groups and to all objectives of the Action.

Exploitation Plan

An exploitation plan will be annually revised by the Management Committee in order to optimize transfer strategies between academia and industry. This plan will identify novel and original technologies and methods, and identify potential collaborations and industry partnerships.

The Action will organise workshops with industry partners and commercialization training events to encourage commercialization of scientific results. These training events will include training on how to start a company, intellectual property and search for strategic partners for commercialization.

Furthermore, having a coordinated European approach will allow for effective communication with policy makers both on national and European levels, as important issues can be identified by the relevant scientific community as a whole.

Finally, the participating research groups will profit from the added value and synergies realised through the collaborative Action. The wider ion-trapping community and non-participating research groups will benefit from the results published in the scientific literature, as well as attending activities periodically organised as part of the Action and through collaborative projects with member groups. The expected results will also be of considerable value for other research communities such as the analytical sciences, biosciences, nanosciences, ion- and plasma physics. These fields will be targeted through publications in the relevant scientific journals and through presentations at scientific conferences.

2.3. POTENTIAL FOR INNOVATION VERSUS RISK LEVEL

2.3.1. POTENTIAL FOR SCIENTIFIC, TECHNOLOGICAL AND/OR SOCIOECONOMIC INNOVATION BREAKTHROUGHS

Research with ion traps offers an extremely high potential for scientific and technological innovation paired with a strong socioeconomic impact. In particular, much is to be expected from quantum technologies in the near future. Indeed, the Quantum Manifesto (http://qurope.eu/manifesto) shows that quantum technologies are expected to be tomorrow's solutions for many scientific and socioeconomic challenges of our society. In the following, a couple of examples for possible innovation breakthroughs are listed:

- The realization of a powerful quantum computer based on ion traps could fundamentally change the way research is done in several fields of science because it enables calculations/ simulations that were not accessible so far.
- The realization of quantum networks (e.g. based on ion traps coupled to other quantum systems) would mark another breakthrough. It would enable, among other things, secure communication which is of socioeconomic relevance.
- Improving the accuracy of atomic clocks (e.g. by another order of magnitude) would drastically open new research directions and many applications. Ultraprecise clocks can be readily turned into ultraprecise sensors for magnetic, electric or gravitational fields amongst others. Thus, the frontier is pushed forward in a broad range of fields, such as testing general relativity, measuring the change of fundamental constants, or even measuring the motion of tectonic plates.

Some of these innovative breakthroughs are highly ambitious and there is a **risk** that these goals will not be completely achieved within the lifetime of the Action. However, since the potential of the innovative breakthroughs is so important, it is worth taking the risk. It can be expected that on the way towards these long term goals, additional important innovations will be triggered which will make the investment double worthwhile. In view of these important breakthroughs, it is now the right time that the European ion trap community teams up to face the corresponding challenges in research. It is probable that scientific progress takes unexpected turns in the next years in the field of trapped ions. The Action Management Team will constantly observe these developments and re-examine which scientific/technological road should be taken and how the workload can be distributed over the participating groups. This will allow a flexibility to find new paths if certain ones turn out not viable.

3. IMPLEMENTATION

3.1. DESCRIPTION OF THE WORK PLAN

3.1.1. DESCRIPTION OF WORKING GROUPS

This Action represent all facets of experimental and theoretical activities in the field of trapped ion physics and its applications. Joining forces will allow to attain a critical mass in manpower and to distribute efforts efficiently among all participants and share technologies and techniques. Complementary challenges can be confronted in parallel, leading to a goal-oriented result-finding process. The Action will draw on existing resources in manpower and equipment which are already available at the partner groups or being funded by complementary sources (universities, national research councils, European Union) in order to fulfil its objectives. The Action will facilitate and accelerate the flow of information, by encouraging mobility of junior and senior researchers, by concentrating interactions through the organisation of thematic workgroup meetings, and by setting up a common interaction platform and database in electronic form, accessible by all participants.

Four Working Groups will be set up, each dealing with a different scientific topic (see below). All efforts will be made to maximise exchange and interaction on certain well-identified topics, to optimise scientific and technological outcomes.

Working Group 1: Tools and Infrastructure

WG1 will start by compiling an inventory of technological issues, which are of concern for most research groups. Information will then be gathered on the various items to build a common knowledge basis. During the annual work group meeting, best practice will be exchanged and a common operational task will be discussed for the following year. This WG has two tasks: tackling cutting edge technological obstacles in a joint manner, to guarantee progress through common means and by simplifying the access to key technologies and experiments, promote the use of ion trapping in a large number of domains. The milestones of this WG are common protocols for ion trap development, a standardisation of general components for ion trap experiments, and compilation of a standard simulation software package.

Working Group 2: Sensors and Precision Measurements

The main task of WG2 is to develop tools and processes for high precision measurements. The first milestone of this WG is the set-up of a database of all experimental, theoretical and simulation results concerning systems for precision measurements and sensors. Further milestones are the proposal, development and realisation of experimental and/or numerical solutions for missing items in the database, and finally the deduction of “universal” procedures and technologies. The annual WG assembly will discuss the proposals of new devices and eventually coordinated efforts to develop these.

Working Group 3: Quantum Control

A third workgroup WG3 will focus on the task of proposing novel protocols for quantum control experiments with trapped ions. This entails the development of high fidelity protocols for quantum gates and their implementation within specific ions. This requires a permanent dialogue between theory, simulation and experiment to propose original and innovating solutions. Milestones of this WG are the development of a common numerical code to simulate ion response to a control, its application to different ions with various energy level schemes, as well as the study of dynamics and thermodynamic effects.

Working Group 4: Hybrid Systems

The efforts of the workgroup will concentrate on the task of advancing the experimental methods to couple trapped ions to other quantum systems, such as neutral atoms or optical cavities. The milestones of this WG include implementation of new experimental approaches to study cooling, ion-neutral interactions, collisions and chemical reactions. In addition, standardised designs, technologies and components for experiments of ions in optical cavities will be compiled and standard components will be shared. Furthermore, other hybrid systems (such as ion-superconductor and ion-microwave systems) and their applications will be explored.

3.1.2. GANTT DIAGRAM

<table>
<tr><th></th><th>WG1
Tools and Infrastructure</th><th>WG2
Sensors and Precision Measurements</th><th>WG3
Quantum Control</th><th>WG4
Hybrid Systems</th></tr>
<tr><td rowspan="4">Year 1</td><td colspan="4">Kick-off meeting of the MC, Set-up of Working Groups</td></tr>
<tr><td>WG1 meeting</td><td>WG2 meeting</td><td>WG3 meeting</td><td>WG4 meeting</td></tr>
<tr><td colspan="4">International Action Conference, Short Term Scientific Missions</td></tr>
<tr><td colspan="4">Set-up of competence database, Progress report</td></tr>
<tr><td rowspan="4">Year 2</td><td colspan="4">MC meeting: scientific evaluation, orientation and schedule</td></tr>
<tr><td>WG1 meeting</td><td>WG2 meeting</td><td>WG3 meeting</td><td>WG4 meeting</td></tr>
<tr><td colspan="4">Training school for early-career investigators, Workshop with socio-economic partners, Short Term Scientific Missions</td></tr>
<tr><td colspan="4">Development of competence database, Progress report</td></tr>
<tr><td rowspan="4">Year 3</td><td colspan="4">MC meeting: scientific evaluation, orientation and schedule</td></tr>
<tr><td>WG1 meeting</td><td>WG2 meeting</td><td>WG3 meeting</td><td>WG4 meeting</td></tr>
<tr><td colspan="4">International Action Conference, Short Term Scientific Missions</td></tr>
<tr><td colspan="4">First collaboration projects with socio-economic partners, Progress report</td></tr>
<tr><td rowspan="4">Year 4</td><td colspan="4">MC meeting: scientific evaluation, orientation and schedule</td></tr>
<tr><td>WG1 meeting</td><td>WG2 meeting</td><td>WG3 meeting</td><td>WG4 meeting</td></tr>
<tr><td colspan="4">Training school for early-career investigators, Workshop with socio-economic partners, Short Term Scientific Missions</td></tr>
<tr><td colspan="4">Monitoring of joint collaborations. Final evaluation and final report – joint review publication</td></tr>
</table>

3.1.3. PERT CHART (OPTIONAL)

3.1.4. RISK AND CONTINGENCY PLANS

As discussed in section 2.3.1 some of the envisaged innovative breakthroughs are highly ambitious and there is a risk that these goals will not be completely achieved within the lifetime of the Action. As examples, mentioned in 2.3.1. the quantum computer, the quantum network and an order of magnitude improvement in the precision of atomic clocks. The following list shows how this risk is mitigated:

Risk	Mitigation strategy
Strong reliance on the funding situation of the countries, which host the respective research groups. (low risk)	To mitigate this, the Action will strongly foster collaborative projects between groups across the network. In addition, sharing know-how, technology and techniques across the network, will naturally enhance the immunity against problems within one area of research.
Low engagement of groups in collaboration and knowledge exchange activities. (low risk)	The Management Committee will constantly monitor activities and engage with participants to ensure efficiency of activities. The activity programme will be modified to adapt to the needs of the participating groups.
Significant difficulties in the research progress. (medium risk)	The Action will explore which alternative scientific/technological road should be taken. The aim is that different groups of the Action try out alternative paths in parallel. This enhances the probability that at least one path leads to success. The large number of ion trap groups in Europe allows for such flexibility in the distribution of tasks.
Industrial partners are not interested in the R&D of technology. (medium risk)	Involvement of many industry partners and continuous effort to foster links with new industry partners.

3.2. MANAGEMENT STRUCTURES AND PROCEDURES

This Action will develop a strong, innovative, dynamic, multidisciplinary European network of researchers who use ion traps for a wide-range of applications. Research topics span a wide spectrum of modern scientific endeavours. The core funding is received through different national programs. COST will be the ideal framework for the realisation of 'horizontal cross-links' as described above to provide added value for each of the sub-disciplines.

The Management Committee (MC) will be in charge of coordination, assessment, impact analysis, and monitoring of the scientific progress of the Action. In addition, a Steering Committee comprised of the Chair, the Vice-Chair, the WG leaders, and the STSM Manager will manage the day-to-day business of the Action. The members of the Steering Committee will be in regular contact to identify possible problems at an early stage, and will meet face-to-face annually, usually at the workshops and/or schools organised by the Action.

Each WG will be coordinated by a WG leader, together with a junior WG leader (ECI). WGs will have an internal email list to simplify discussions. An annual face-to-face meeting will be held per WG for a period sufficiently long enough to allow for discussions but not longer than 3 days. During this meeting which is dedicated to one pre-defined operational task, recent scientific results will be presented. At least one "brain-storming" discussion will be scheduled to encourage the emergence of novel experiments, protocols or approaches; and a round-table discussion with an evaluation of past activities and steering of future tasks will be organised. In view of the common interest of WGs in certain topics, some WG meetings will be organised as joint meetings to facilitate discussions between WGs.

The aim is to organize two international conferences during the lifetime of the Action, which will unite the whole community (scientific and socio-economic partners). The final workshop will eventually be held jointly with a larger international conference to allow for substantial dissemination of the Action's results.

To achieve the best coordination of the participating research teams, exchanges on all levels (PhD students, postdocs, senior scientists) will be facilitated between research groups. Mutual visits of (young) researchers for periods ranging from a few days to a few weeks will allow efficient collaboration on certain subtopics and will strengthen the ties between the member groups.

Annual workshop meetings for all the participating research groups, as well as dedicated events with socioeconomic partners, also contribute to maximise interaction and discussions. Quantum technologies are rapidly evolving and there is a large demand for training events. Training schools will contribute to the training of younger researchers, the Action will aim to organize at least two during the lifetime of the Action. The thus established personal contact and connections will form the basis for successful future collaborations. In addition, shorter tutorials on specific themes will be proposed at every WG meeting.

The MC will be in charge of piloting and evaluating the ongoing Action by checking against the identified milestones. Evaluation will concern all of the activities cited earlier in this section, in terms of their efficiency and scientific output. This will be scheduled twice a year, in order to encourage or eventually re-structure certain topics, and to maintain an overall stability of the research carried out, with respect of the defined objectives.

The MC will also be responsible for the dissemination of results throughout the whole community. Moreover, it will prepare and organise the dissemination of results to a wider scientific community, and in particular to interested new groups. The MC will be scrutinising eventual collaboration partners and will be responsible for proposing new contacts in order to give new impulses and ideas. The MC will in particular encourage the emergence of novel scientific topics and applications.

3.3. NETWORK AS A WHOLE

At the proposal stage, the COST Action is a concerted effort of a large number of research groups from about 20 COST countries, including several COST Inclusiveness Target Countries. Amongst them are the leading groups in their respective fields but also a variety of smaller and new groups. The Action will strive to balance research groups and to encourage emerging ideas and projects. By bringing experts from different areas together, the Action will facilitate the adoption of techniques from one research area in others.

The Action is designed to be open, encouraging the interaction with neighbouring (and other) fields, to foster novel ideas and innovation. A dedicated effort will be made to bring together scientists working on "uncommon" or emerging topics, to promote brainstorming and exchange of competences and know-how. The Action will encourage the multiplication of formal research projects, and expects to reach a high leverage factor. The budget invested in collaboration events will directly trigger a large off-spring of project funds from various European and (bi-) national sources. A 'spin-off' mentality will also be promoted by encouraging scientists to commercialise their ideas.

The interaction with international partners is an important aspect and will be encouraged in particular for the exchange of ECI through STSM but also via participation in all events. Interaction with existing COST Actions (e.g. MP1403) will be sought, in order to explore possible common activities.